CRG

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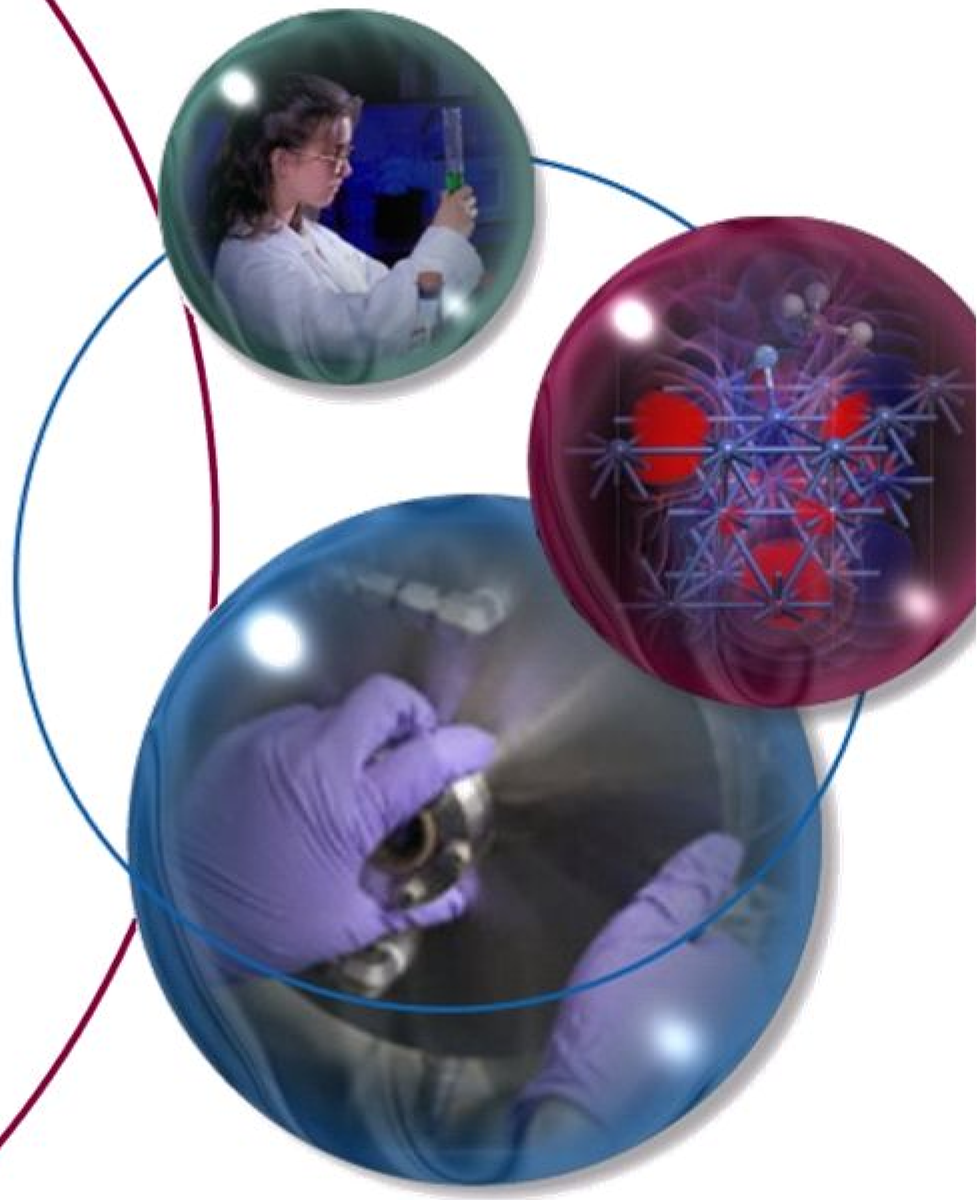

Composite Mirror Technology

19 September 2006

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Acknowledgement

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Overview

- Introduction
- Materials
- Processes for Replica Optics
- Mirror Structures
- Summary

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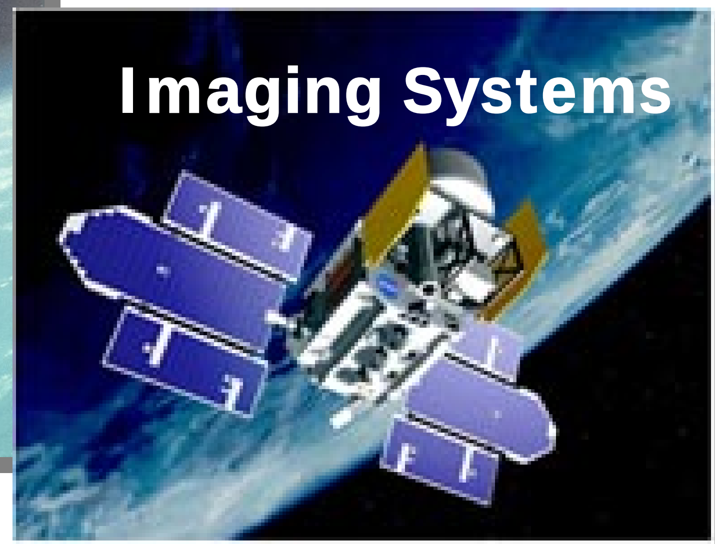
Introduction

- **Applications: Space-Based Optics**



- **Operational Need: Improve on glass & metal mirrors**
  - **Lighter**
  - **Tougher**
  - **Cheaper**

Images
L: www.fas.org/spp/starwars/program/sbl.htm
R: www.ball.com/aerospace/prod rs bus.html

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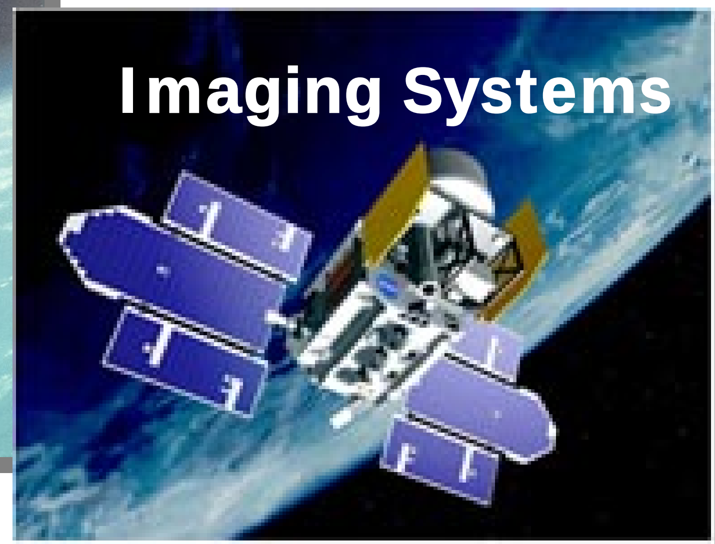
Introduction

- **Applications: Space-Based Optics**



- **Operational Need: Improve on glass & metal mirrors**
  - Lighter
  - Tougher
  - Cheaper

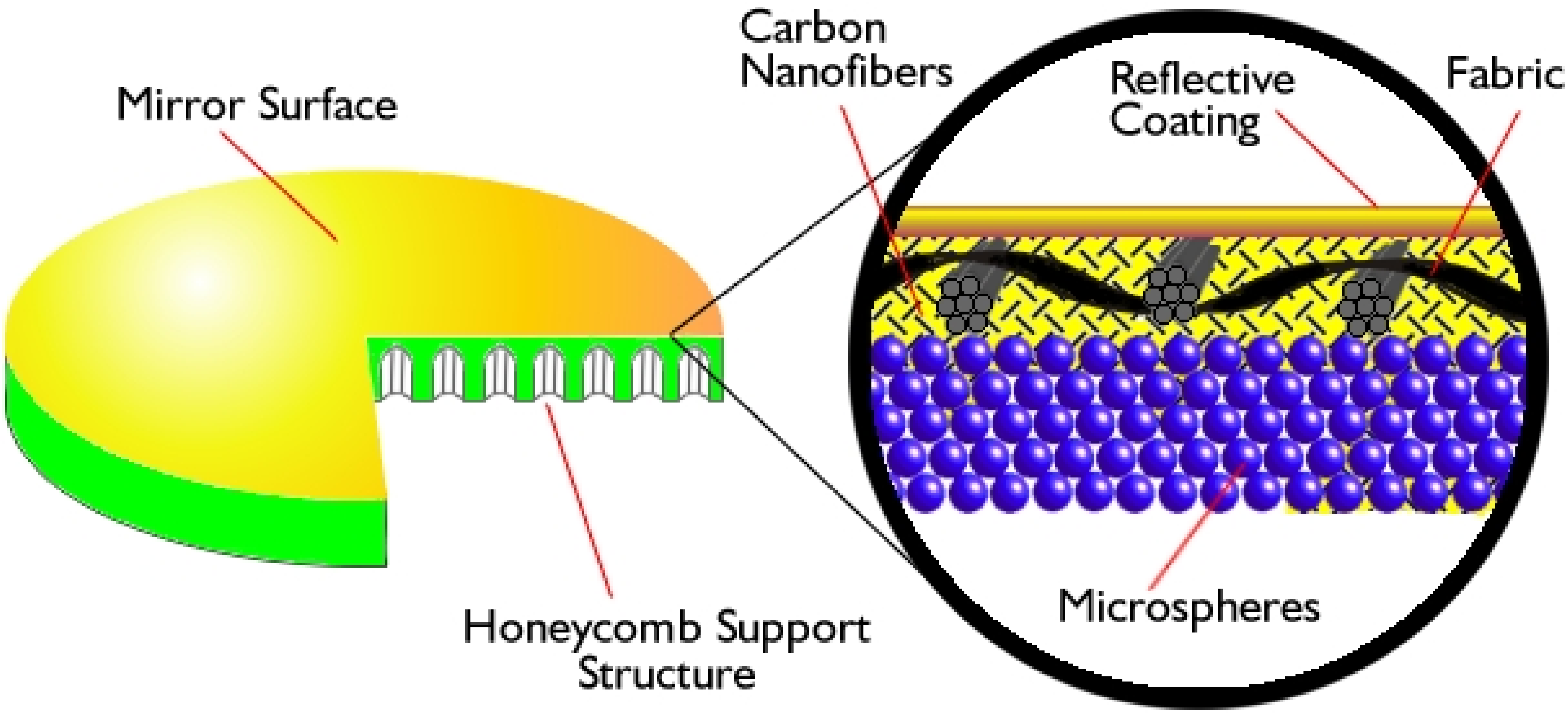
$\boxed{\text{new materials}}$ (Lighter, Tougher)

new processes (Cheaper)

Introduction: Material Design Elements

- **Space compatible:**
  - Radiation hard (to space ambient)
  - AO resistant (inherent or through practical coating)
  - Resistant to out-gassing in vacuum
- **Improvement over glass or metal mirrors:**
  - Lower areal density
  - Higher tolerance to thermal excursion (low CTE)
  - Improved strength (toughness & stiffness)
- **Compatible with obtaining optical surface**

Multi-Component Composites



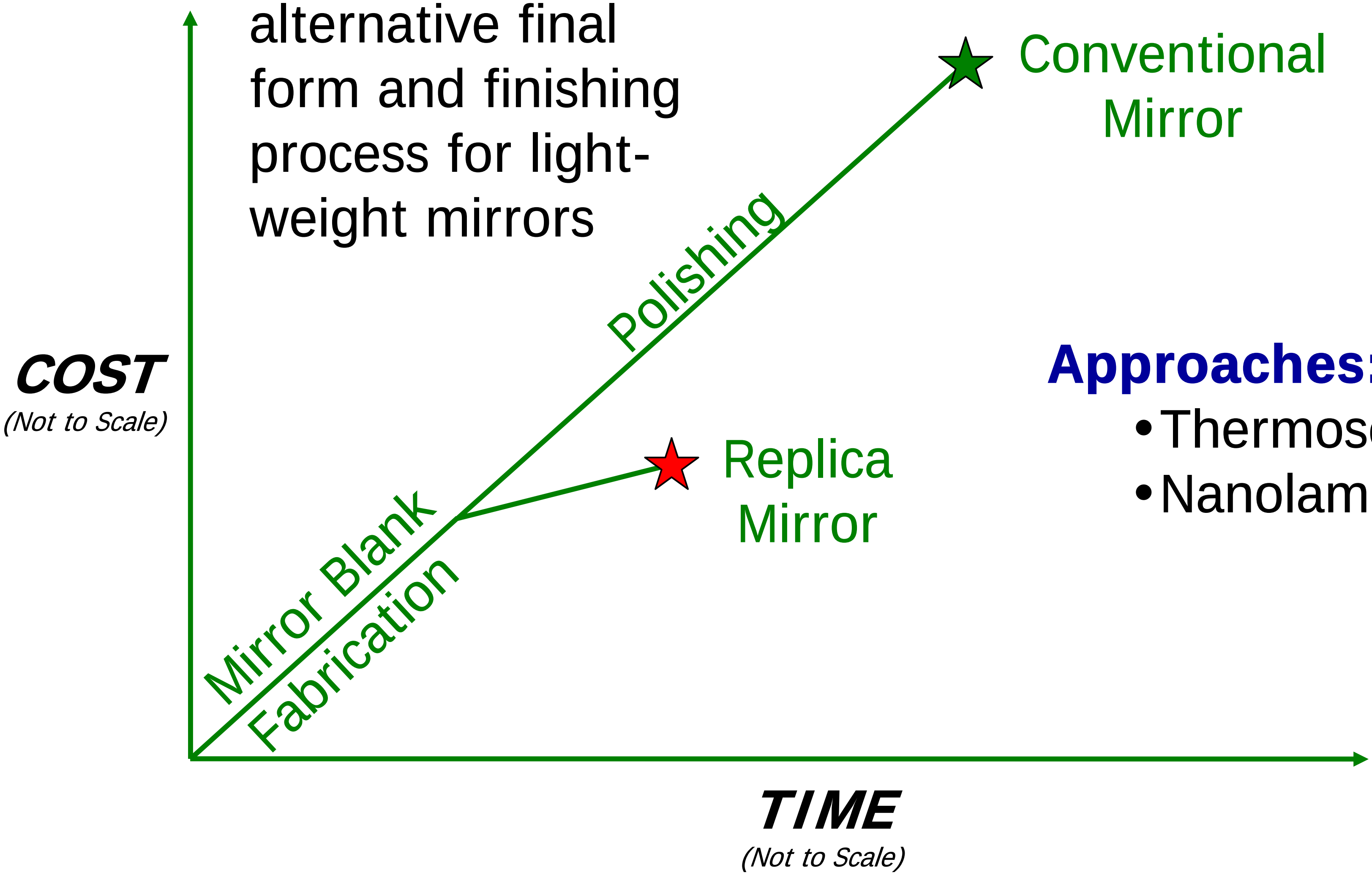
Introduction

- **Applications: Space-Based Optics**

- **Operational Need:**
  Improve on glass & metal mirrors
  - Lighter → new materials
  - Tougher → new materials
  - Cheaper → new processes

Introduction: Replication Technology

Goal: Develop alternative final form and finishing process for light-weight mirrors



Approaches:

- Thermoset
- Nanolaminate

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Overview

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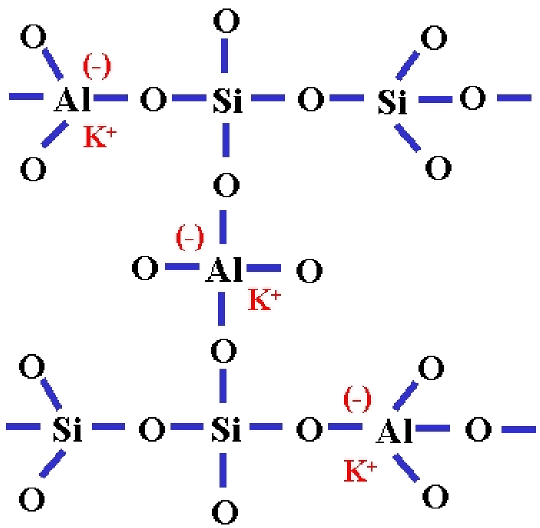
Materials: Sialyte™ Inorganic "Resin"



poly(sialate-siloxo)

Attributes

– Inherently space compatible

– Lattice structure: high stiffness

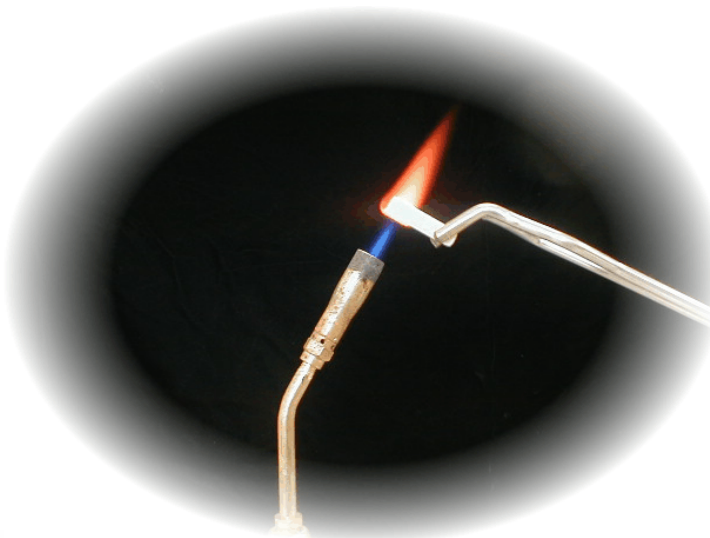
– Operating temp: to ~900 ^{o}C bridges gap between organic resin and ceramics

– Low-temp process: fabrication savings

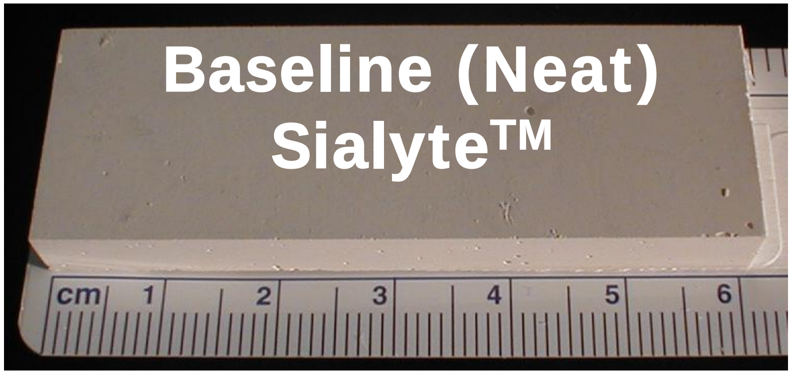
Applications

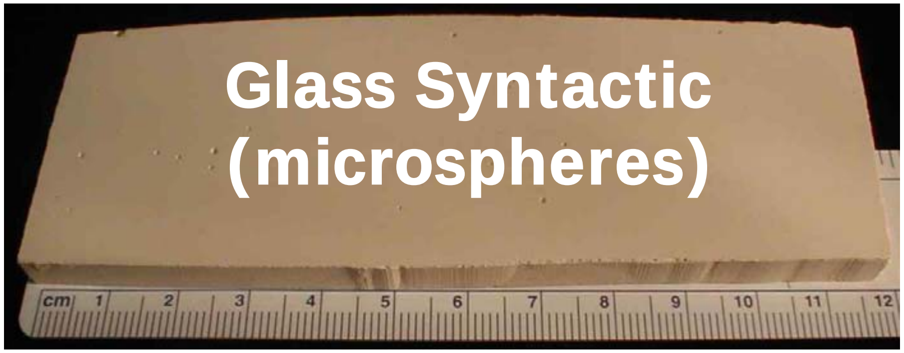
– Space-based structures

– Propulsion components

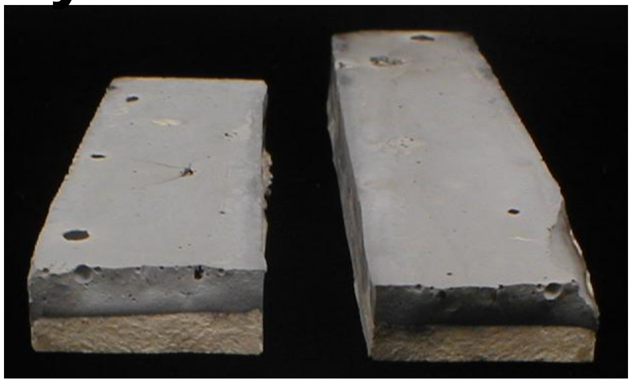


Materials: Candidate Sialyte™ Composites





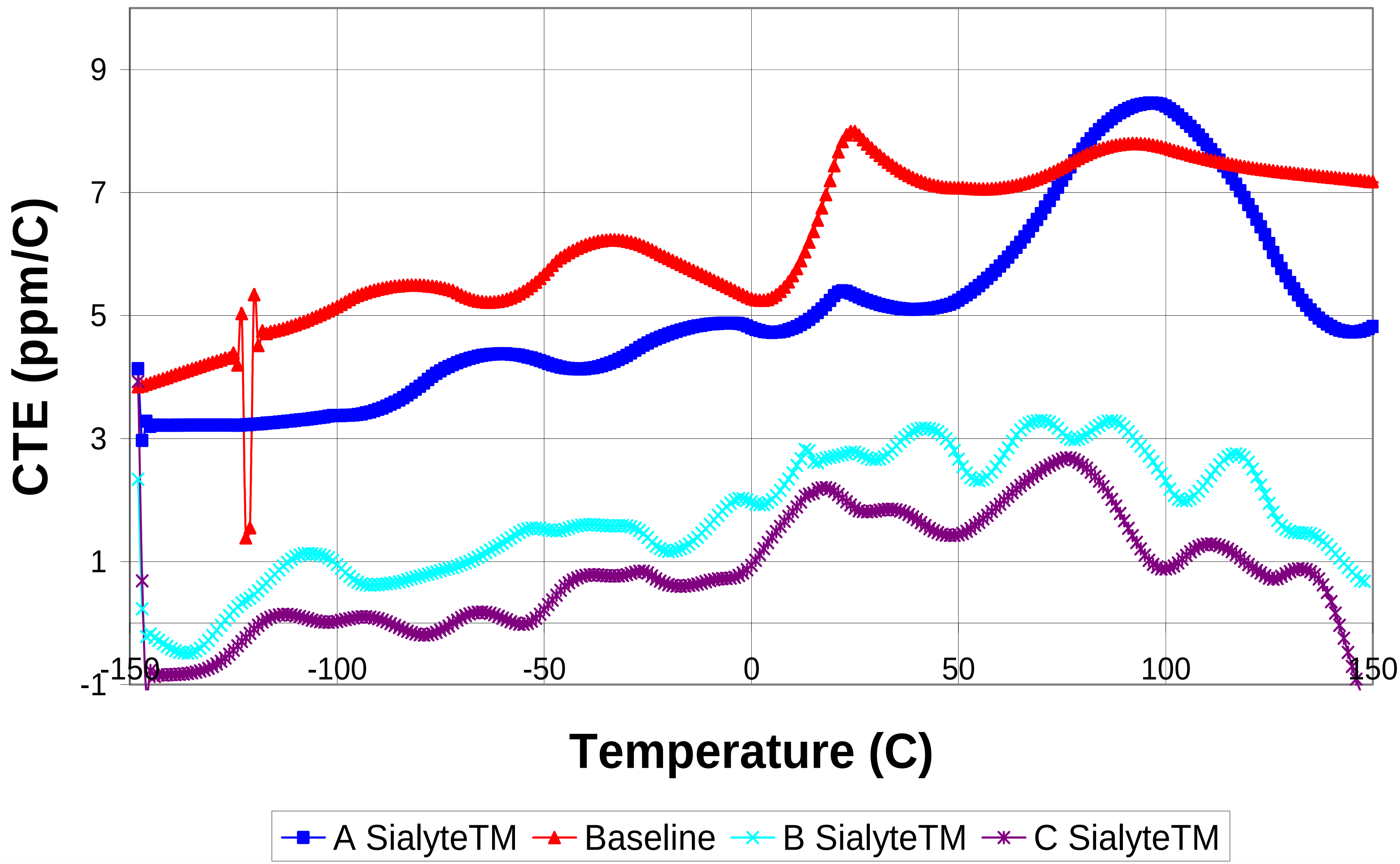
Carbon Nanofiber-Glass Syntactic Laminate



Materials:
Candidate Sialyte™ Composites

Moderate process scale-up & composite optimization

Materials: Sialyte™ CTE Tailoring



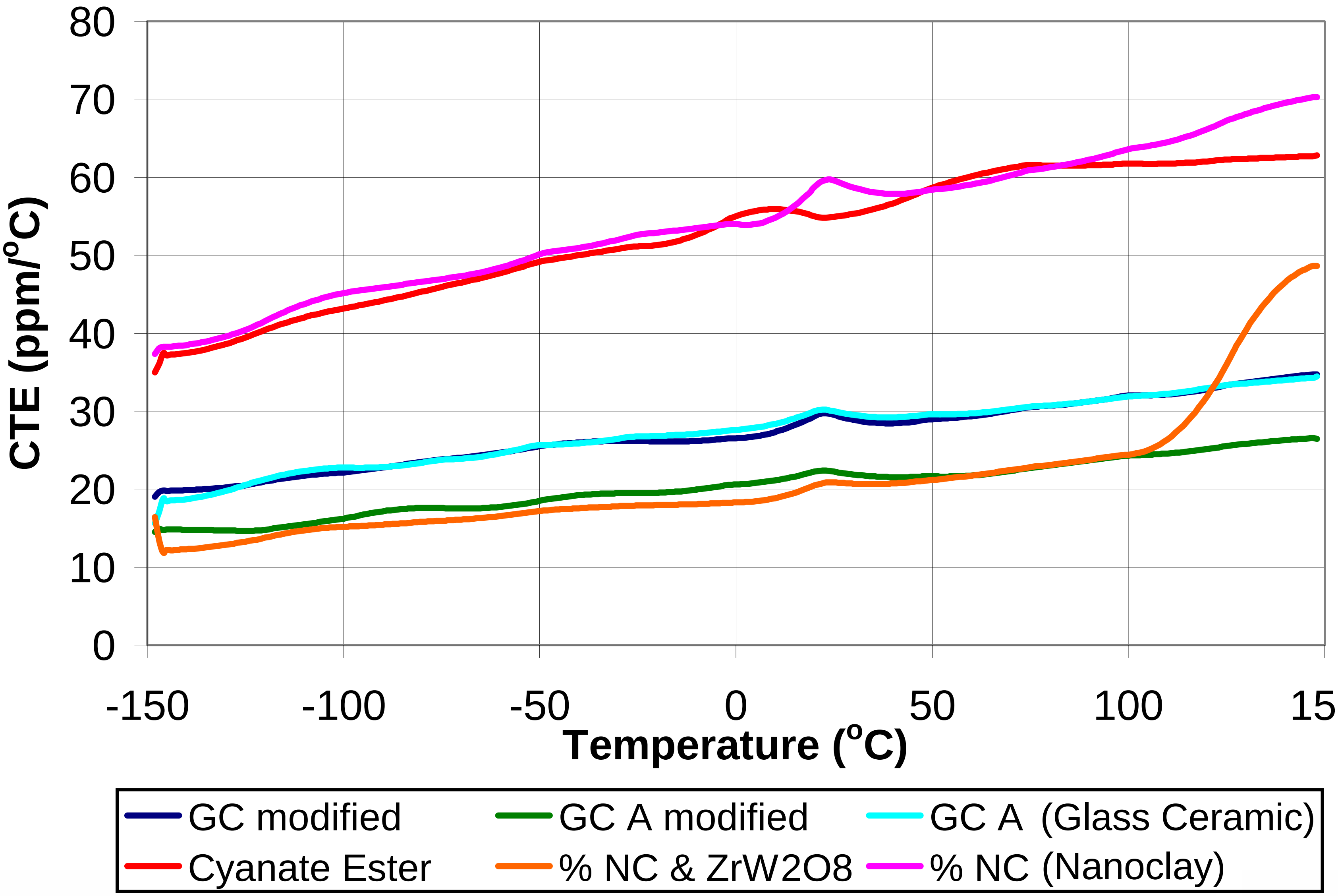
Materials: Cyanate Ester Organic Resin

- Demonstrated space-compatible chemistry
- Compatible with mature processes demonstrated with epoxy-based materials
  - Streamlines composite design
  - Streamlines process development
- Formulation experience:

  Confidence in near-term transition

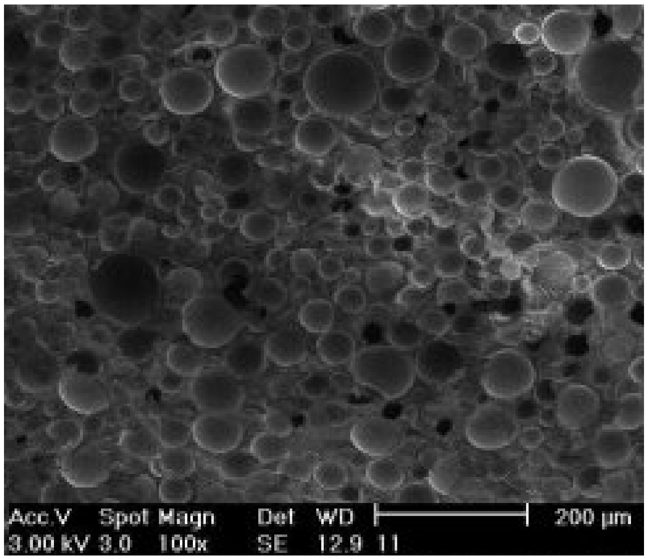
Materials: Cyanate Ester Organic Resin

Negative CTE powders reduced CTE by more than 50 %



Materials: Cyanate Ester Syntactic Foam

"Syntactic" = resin matrix + hollow microspheres



Attributes

– Low mass density: 0.55 g/cc
– High specific strength:
  126 MPa in compression
– Simple fabrication processes

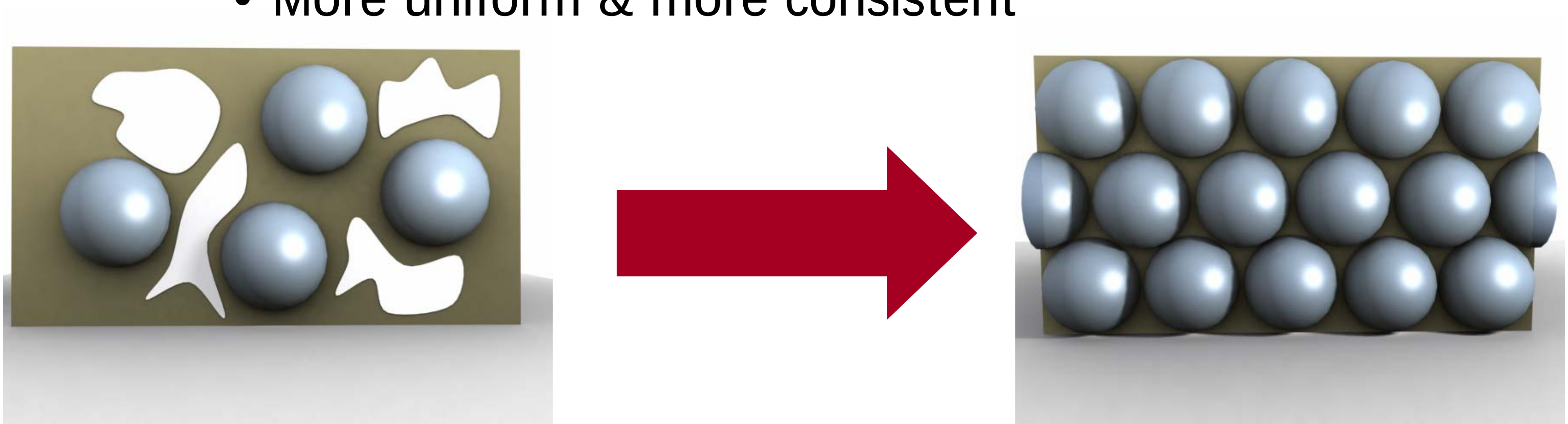
Applications

– Lightweight structures
– Low dielectric structures
– High strength insulation

Materials: Cyanate Ester Syntactic Foam

New fabrication technique

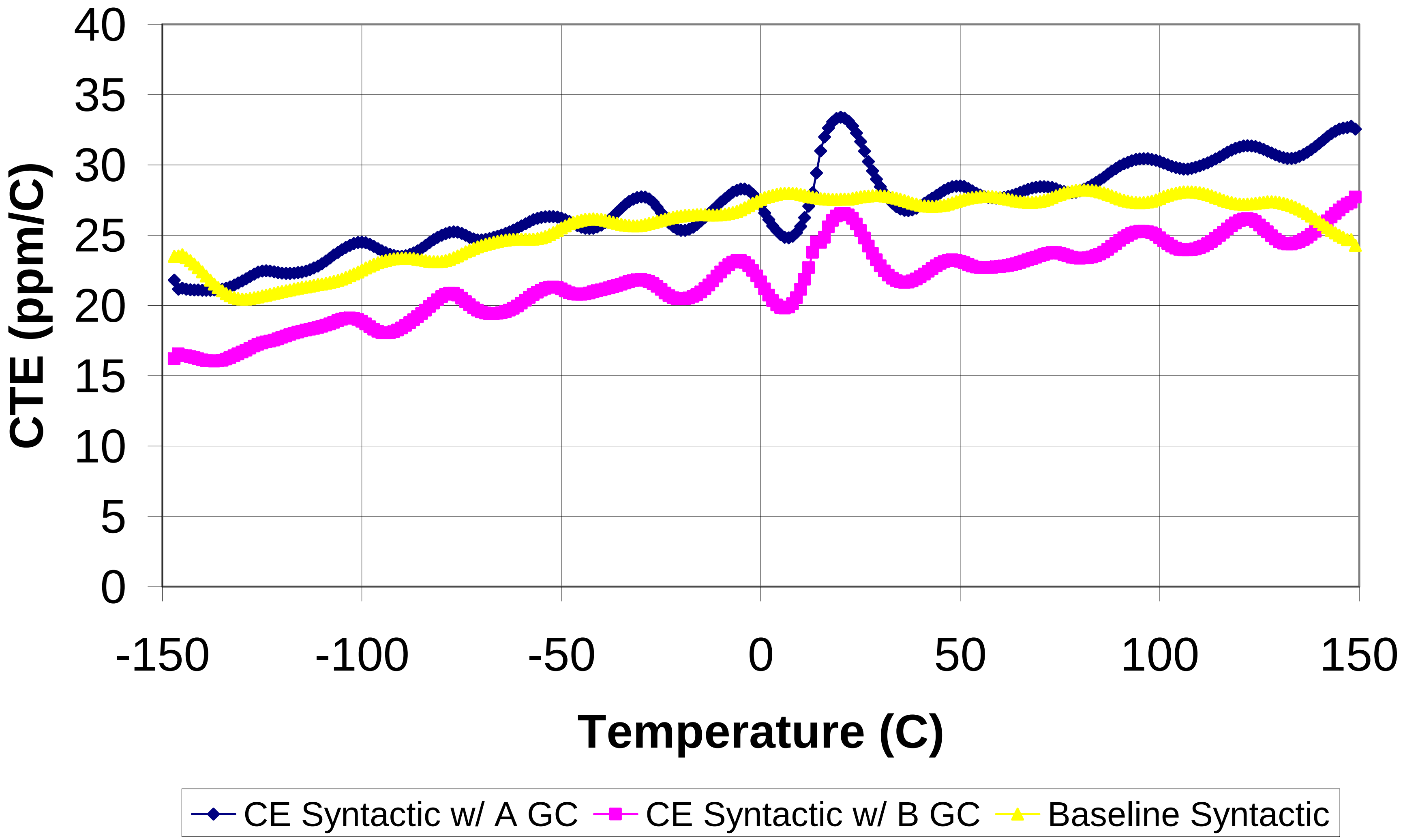
- Eliminates voids & increases microsphere loading
- Improved material properties
  - Stronger
  - More uniform & more consistent



Conventional Process | **CRG Process**

Materials:
Cyanate Ester Syntactic Foam

Syntactic CTE Tailoring

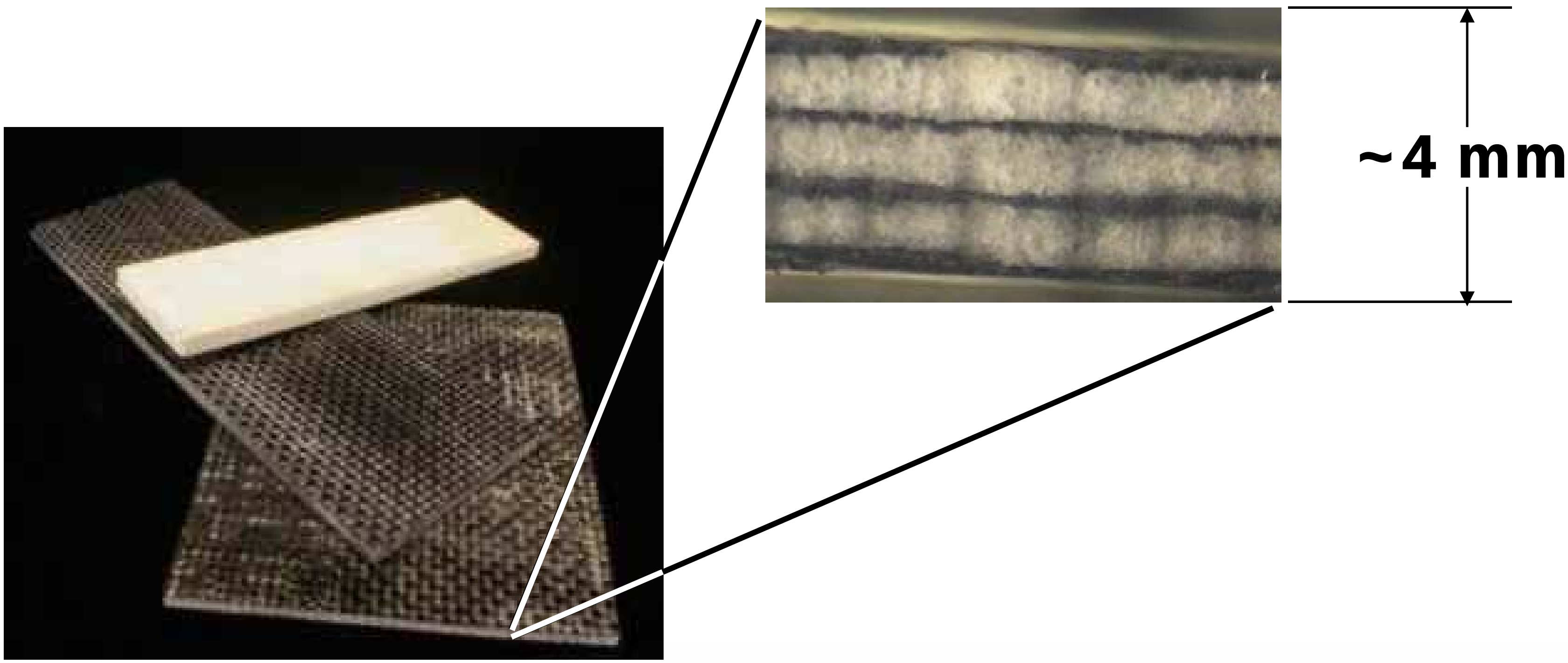


Materials: Synlam™ Composite

Synlam™ developed for mirror structure:

syntactic **lam**inate composite

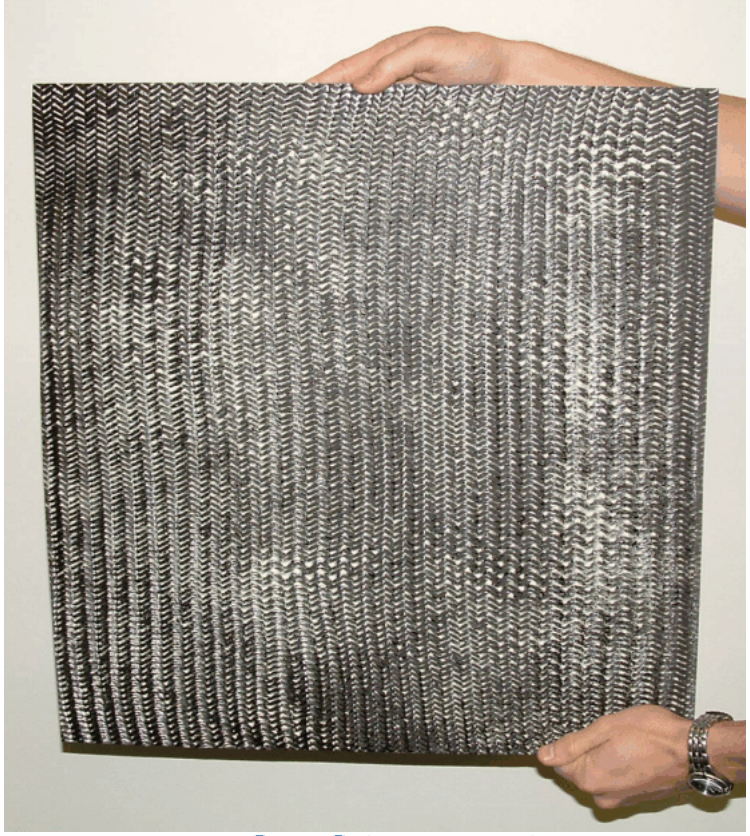
- Cyanate ester - glass syntactic sandwich cores
- Cyanate ester - carbon fiber-reinforced face sheets

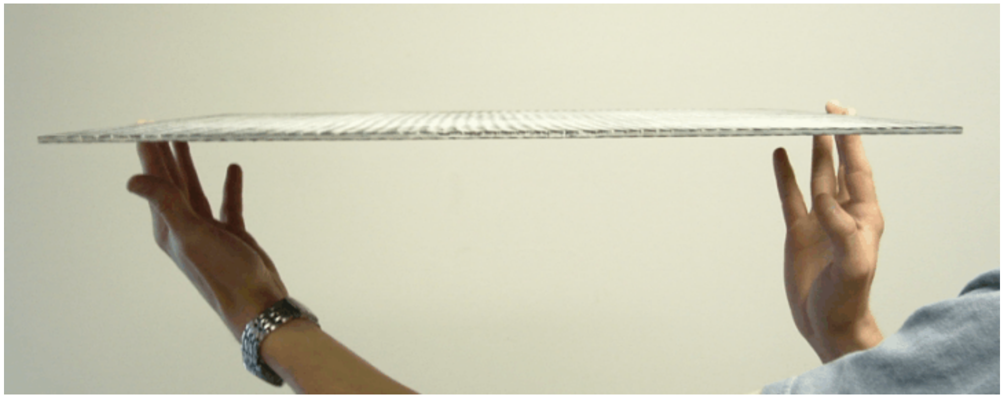


Materials: Synlam™ Composite

Cyanate Ester Synlam™

– Lightweight
– Competitive specific stiffness
– 200 °C max operating temperature





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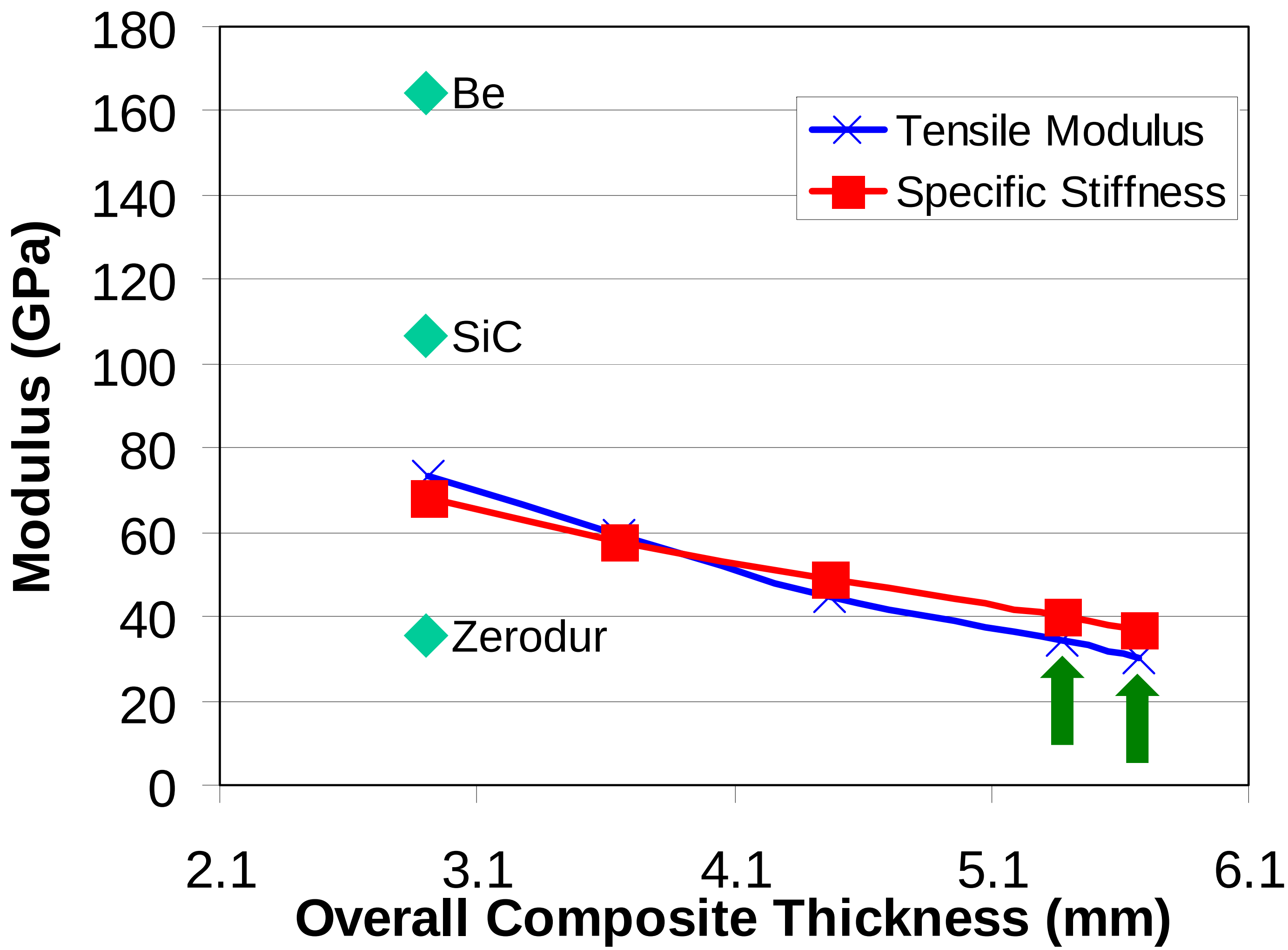
Materials: Synlam™ Composite

Thickness vs Tensile Modulus* & Specific Stiffness



* ASTM D3039 Data points with limited sample set Ref Specific Stiffness

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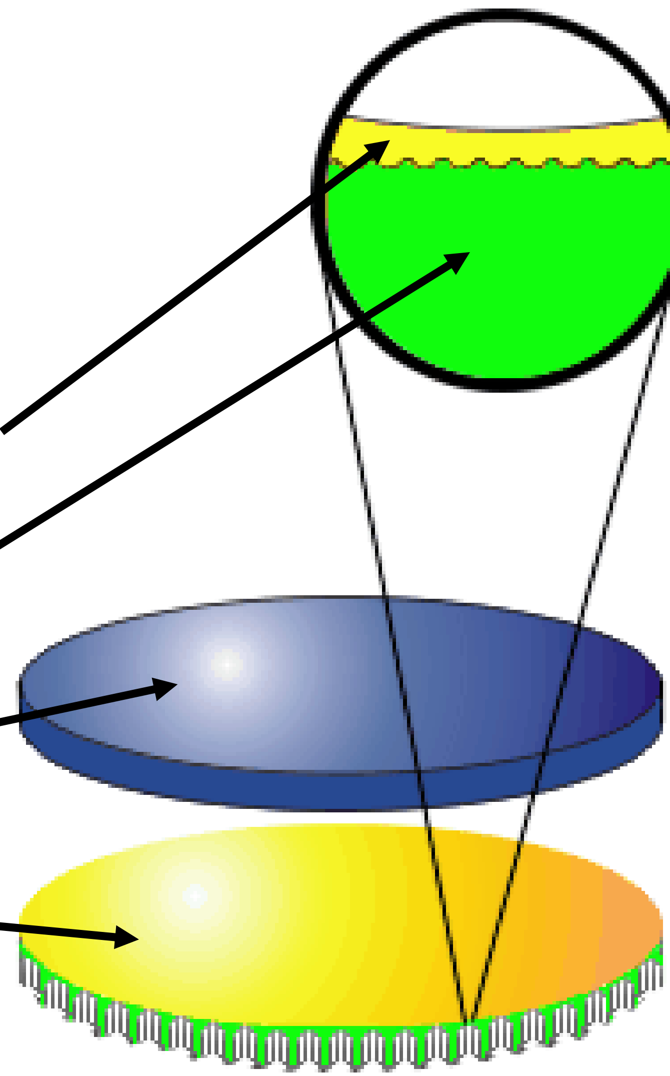
Processes for Replica Optics: Thermoset Replica Concept

Cast Optical Surface (no grinding or polishing)



Polymer Mirror Surface

Mirror Substrate

Optical Quality Reusable Mold

Released Composite Mirror (final figure & finish)

Processes for Replica Optics: Sialyte™ Replica Mirror Coupon

Fabrication

- Sialyte™ cast on optical flat
- Gold coating

Finish

- Porous surface
- Roughness:
  - Best local: ~5 nm RMS (neat)
  - Best overall: ~8 nm RMS (ZrO_2 composite)

Sialyte™ replicas deferred in favor of cyanate ester

Processes for Replica Optics: Cyanate Ester Surface Replication

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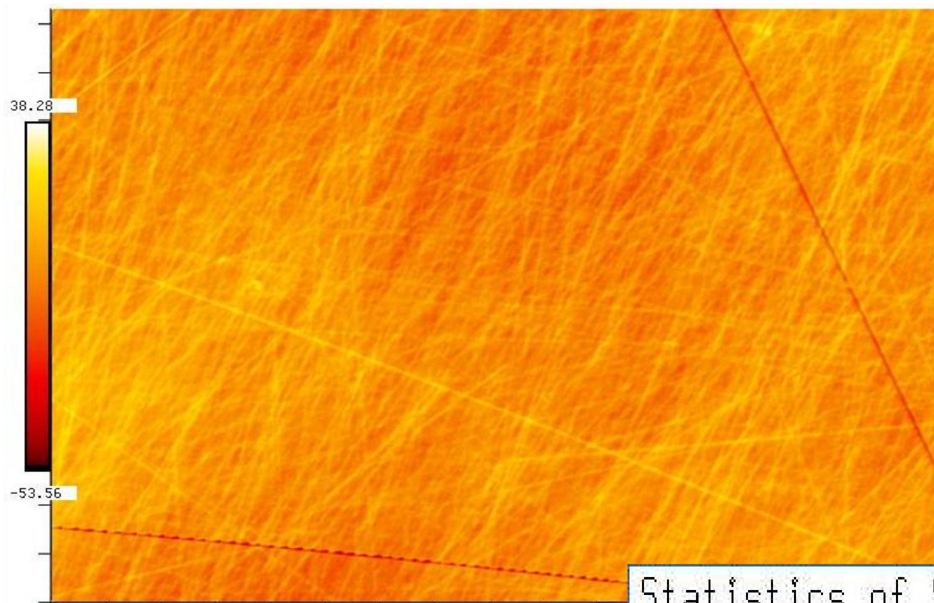
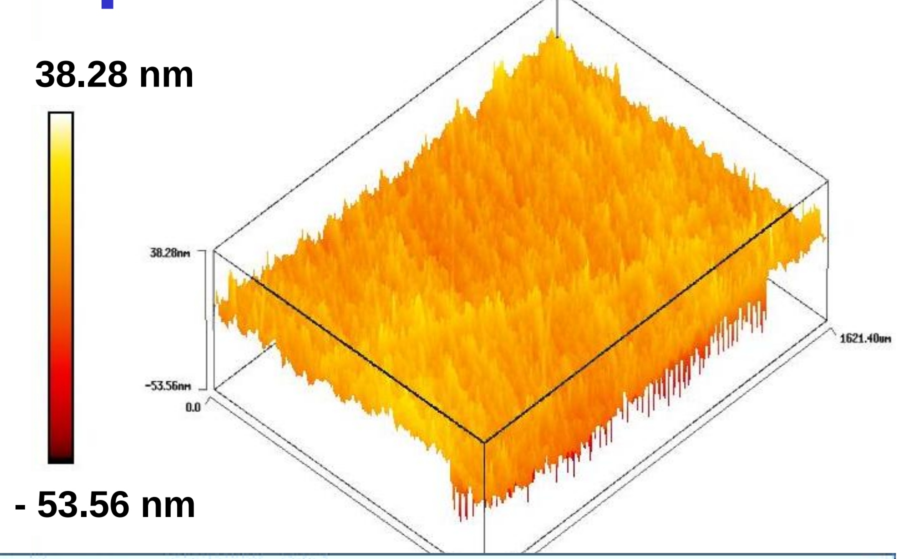
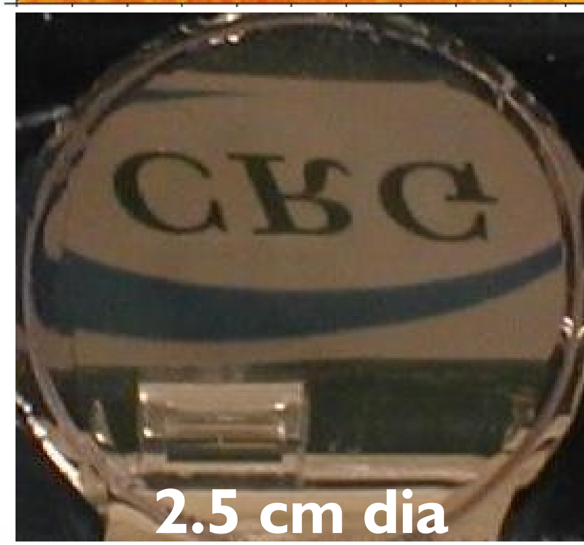
Replica Surface





Statistics of Surface:	GK40-1A				
Rp:	38.28nm	Rq:	6.09nm	Area:	1621.40x1235.00um
Rv:	-53.56nm	Ra:	4.74nm	Mag :	5.0
PV:	91.84nm	Rsk:	0.05	DATE:	06-14-2002
PT:	350071	Rku:	4.45	TIME:	10:03:38
Terms Subtracted:		Tilt			



Surface Roughness: 6.09 nm RMS

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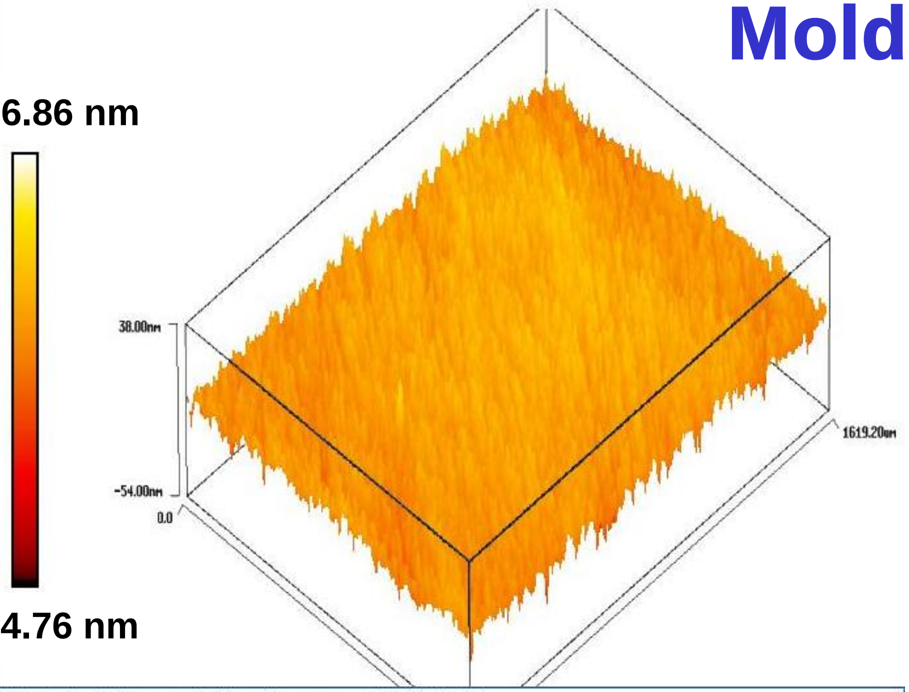
Processes for Replica Optics: Cyanate Ester Surface Replication

Mold Surface

26.86 nm

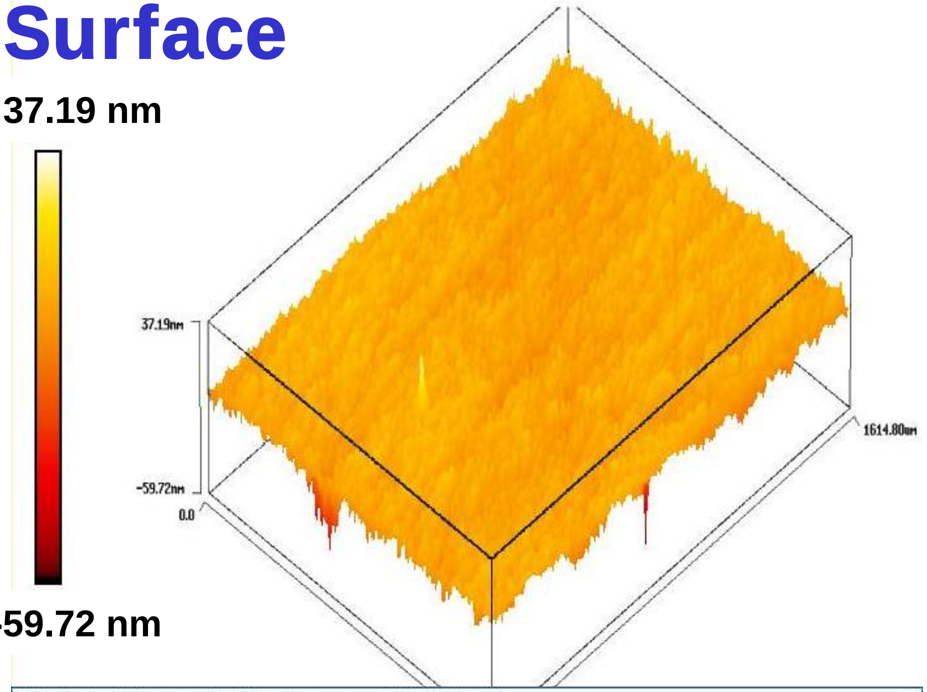


-34.76 nm

Statistics of Surface:		PUCK1-A	
Rp: 26.86nm	Rq:	5.41nm	Area: 1619.20x1229.80um
Rv: -34.76nm	Ra:	4.30nm	Mag : 5.0
PV: 61.62nm	Rsk:	-0.19	DATE: 06-13-2002
PT: 348127	Rku:	3.16	TIME: 09:29:50
Terms Subtracted:	Tilt		

Roughness Before Casting: 5.41 nm RMS

37.19 nm



-59.72 nm

Statistics of Surface:		PUCK1-B	
Rp: 37.19nm	Rq:	4.61nm	Area: 1614.80x1229.80um
Rv: -59.72nm	Ra:	3.59nm	Mag : 5.0
PV: 96.91nm	Rsk:	-0.65	DATE: 06-14-2002
PT: 347182	Rku:	5.65	TIME: 11:56:13
Terms Subtracted:	Tilt		

Roughness After Casting: 4.61 nm RMS

Processes for Replica Optics: Cyanate Ester Syntactic Mirror

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Objective

Demonstrate feasibility of direct casting on optical mold (optical flat for this trial)

Results

Figure

Slight curvature (due to cure shrinkage)

Finish

- Good mold replication
- Good reflective surface

Fabrication Process

- Good mold release
- Process development needed to improve figure replication

Processes for Replica Optics: Cyanate Ester Syntactic Mirror

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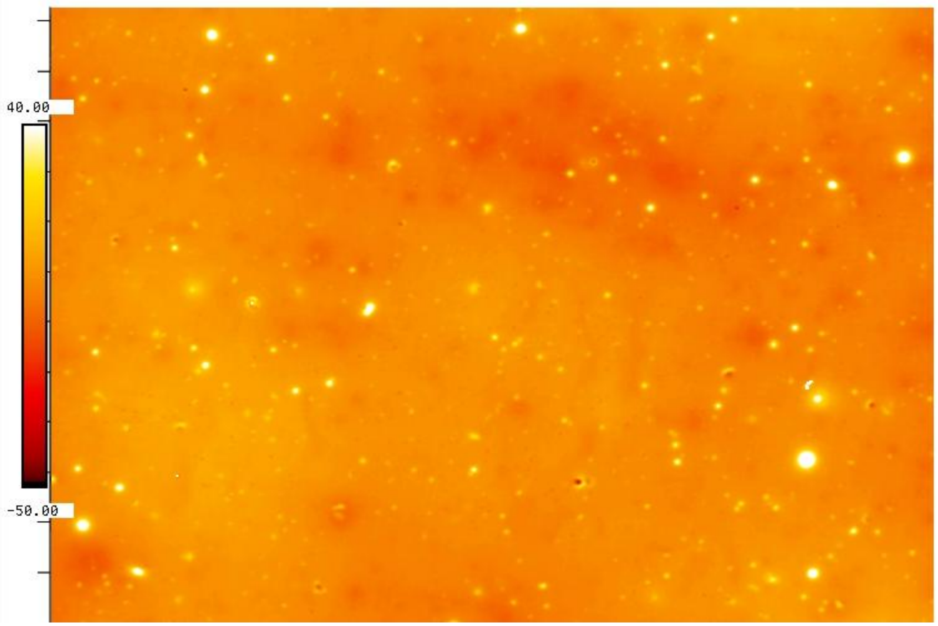

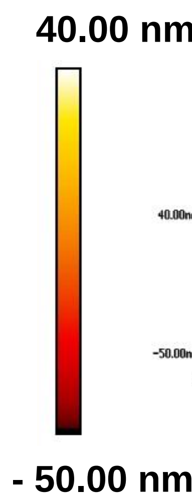

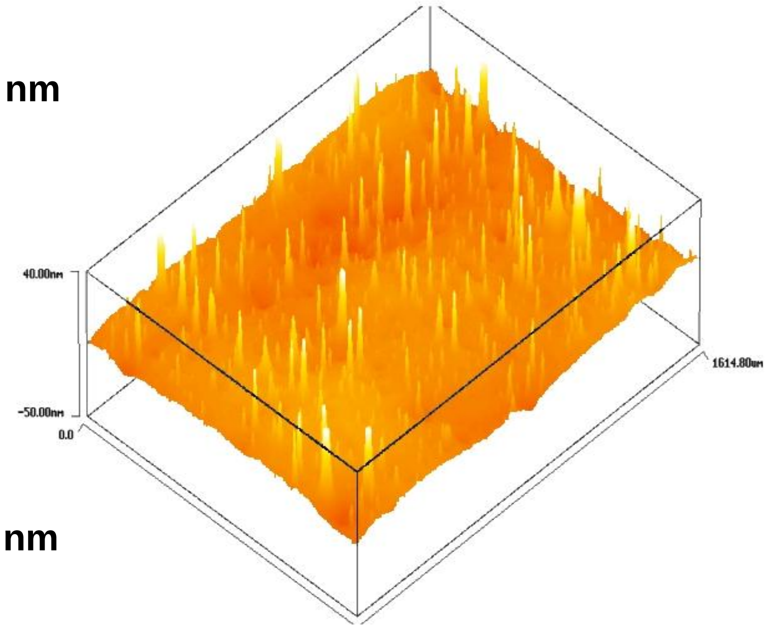

Statistics of Surface: GK84-B					
Rp:	166.37nm	Rq:	5.15nm	Area:	1614.80x1229.80um
Rv:	-32.51nm	Ra:	3.29nm	Mag :	5.0
PV:	198.88nm	Rsk:	5.13	DATE:	09-05-2002
PT:	347168	Rku:	91.18	TIME:	15:18:39
Terms Subtracted:		Tilt			

Surface Roughness: 5.15 nm RMS

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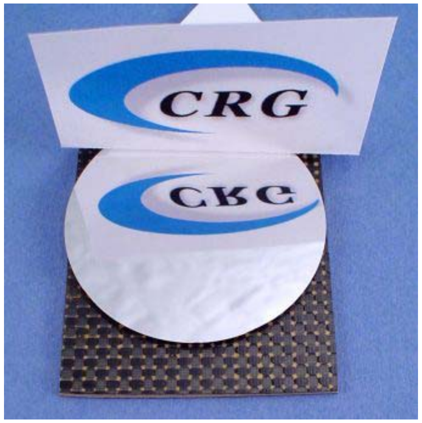
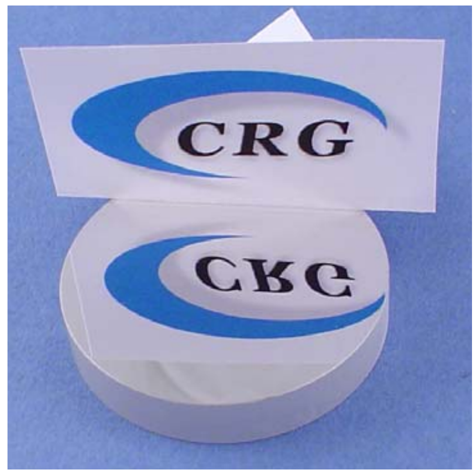
Processes for Replica Optics: Mirrors on Synlam^{TM} Substrates

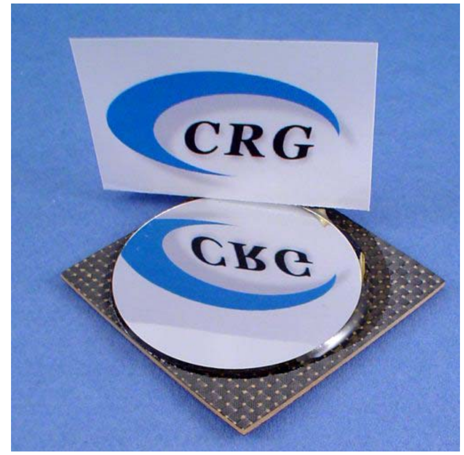
Cast Thermoset Replication



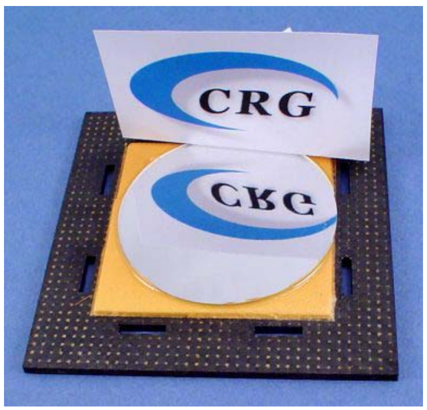
Early Mirror (Print-through)



Mold with Release Coating



Mirror w/CE Resin Buffer Layer



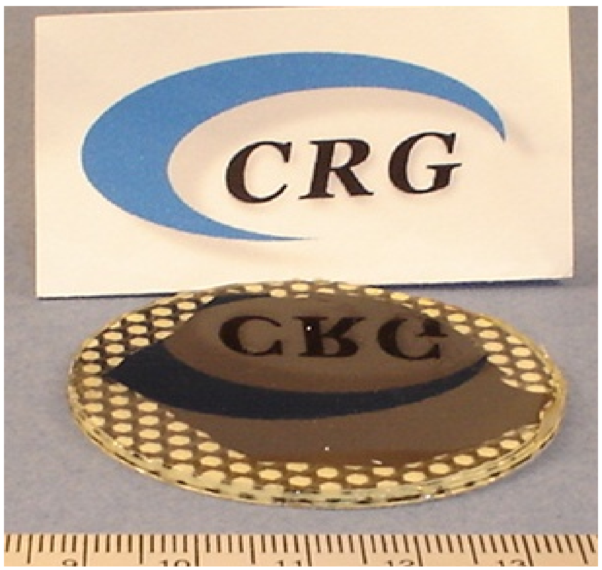
Mirror w/Syntactic Buffer Layer

Mirror on CE MWNT Composite

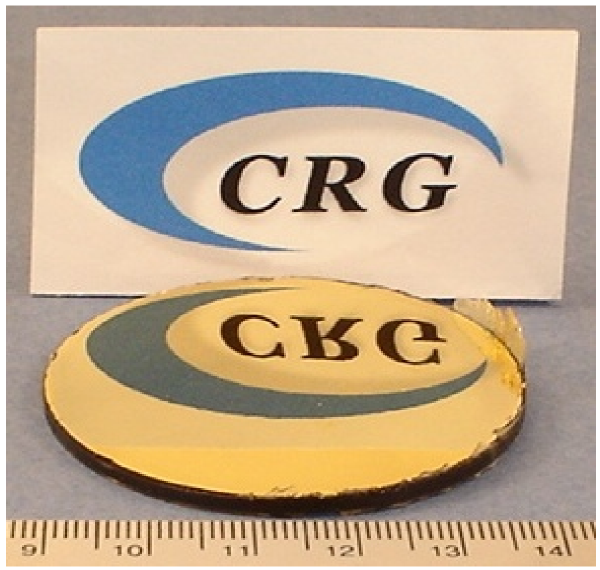
Processes for Replica Optics: Mirrors on Synlam™ Substrates

Mitigating fiber print-through

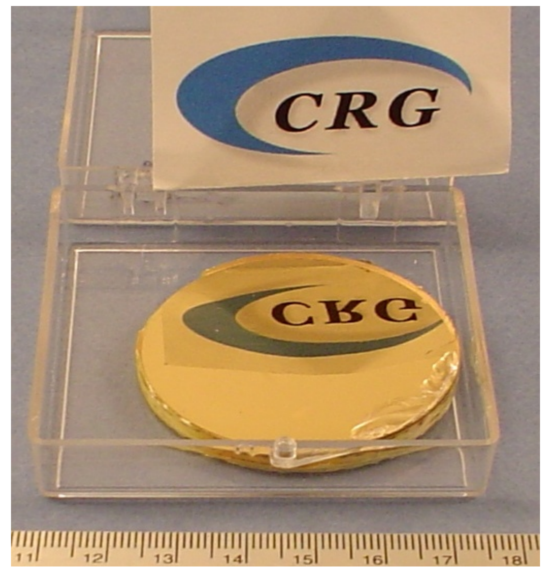
- Original roughness (no buffer) >150 nm RMS
- Adding buffer layers reduces roughness
- Trade-off between figure and finish



66.9 nm

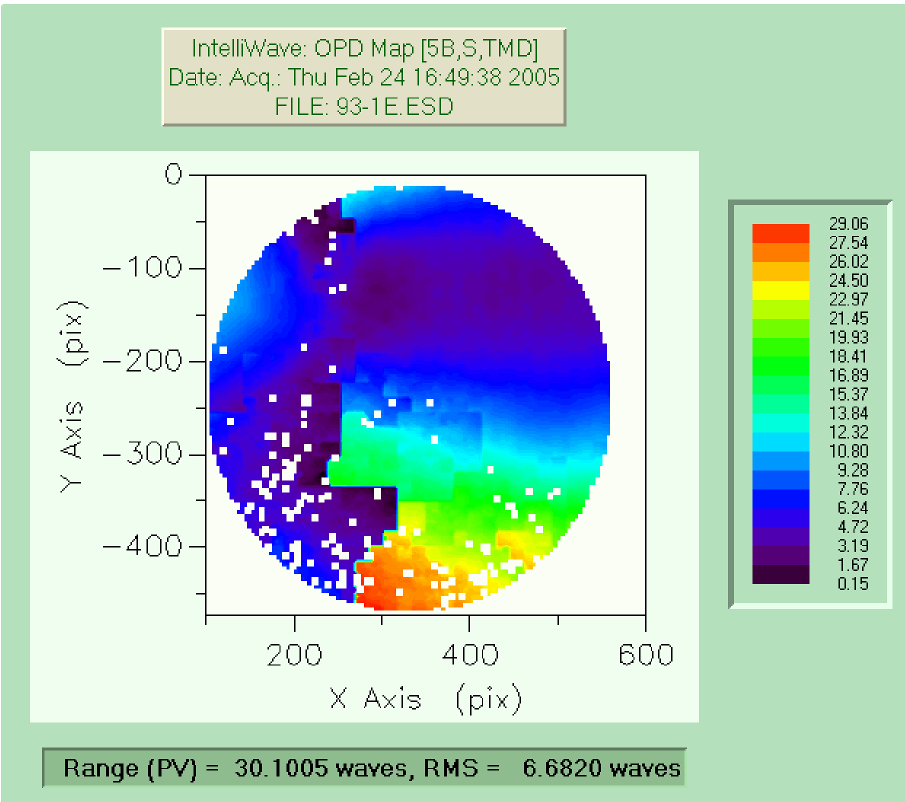


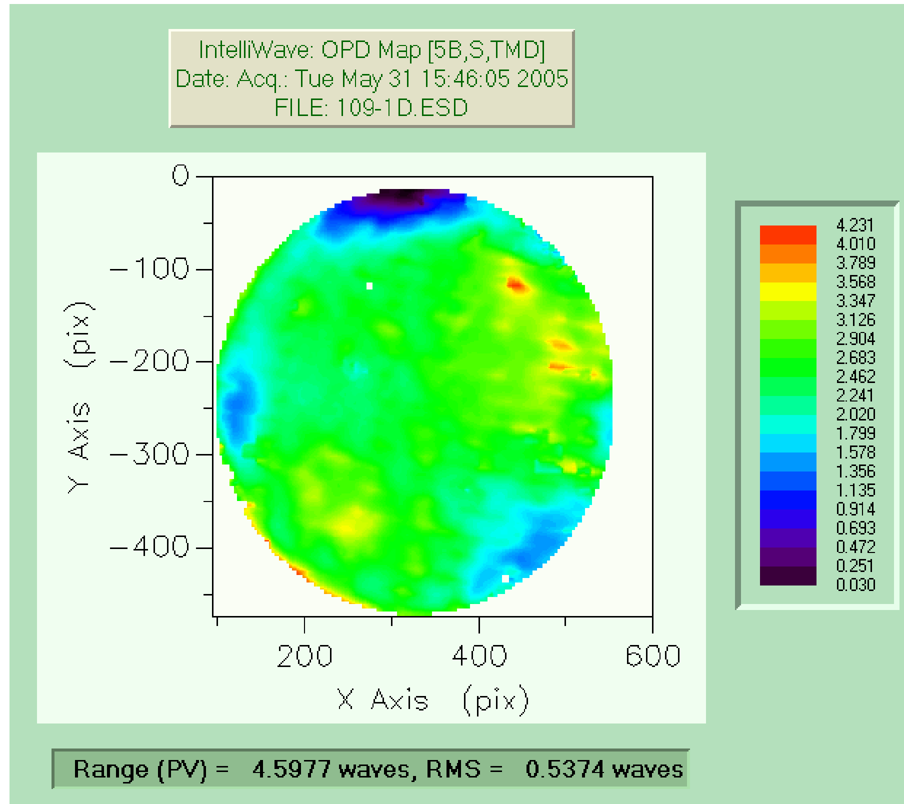
77.7 nm



10.2 nm

Processes for Replica Optics: Mirrors on Synlam™ Substrates



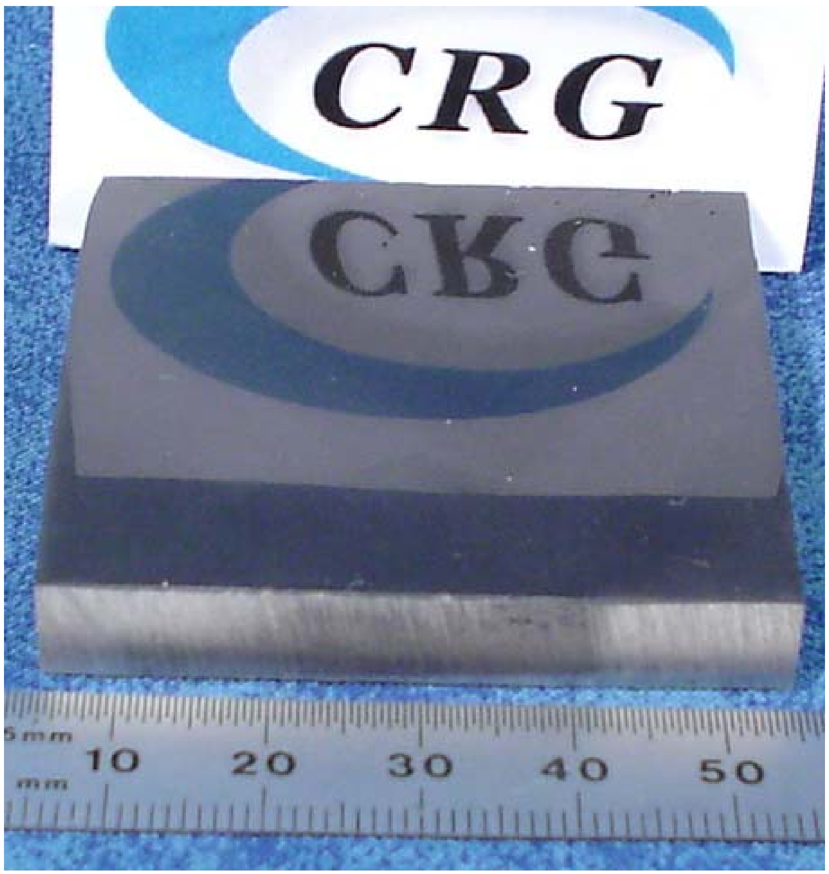


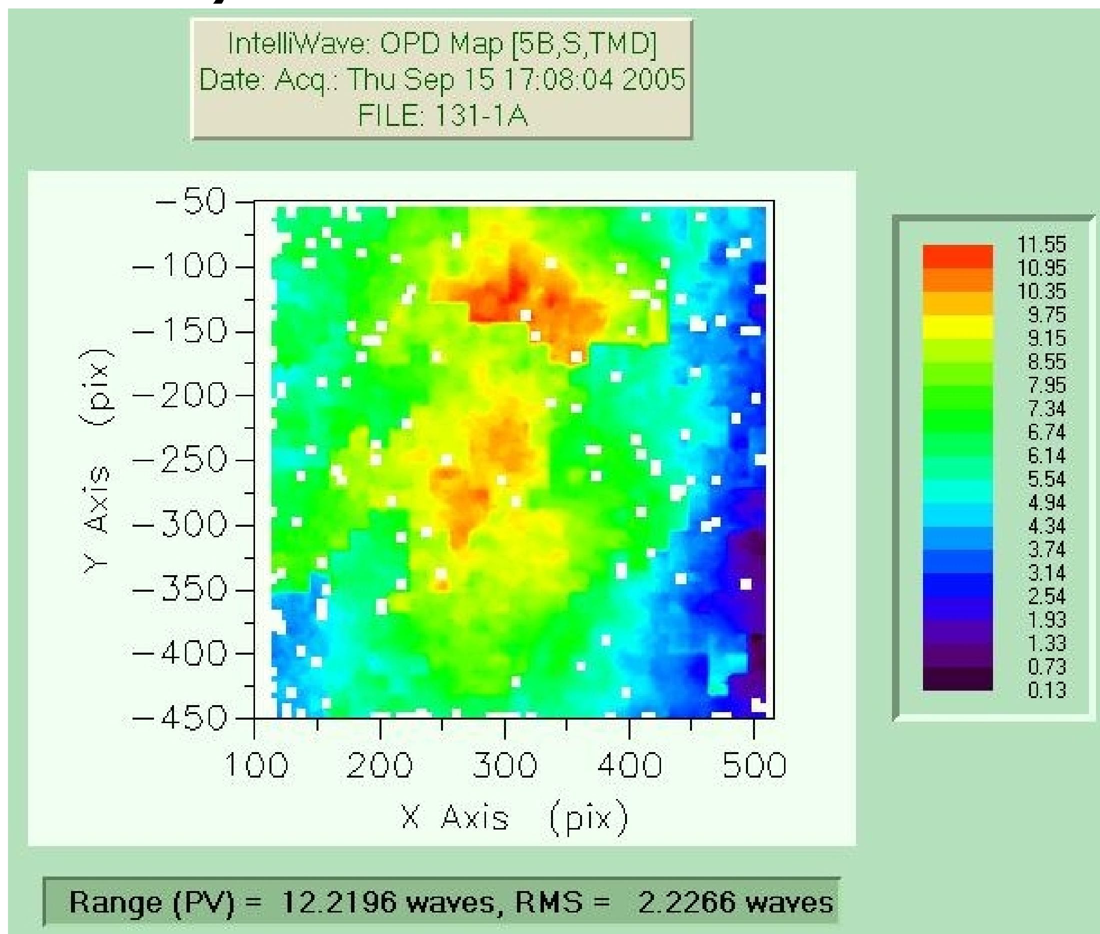
Optical surface on early Synlam™ substrate: 6.7 waves

Optical surface on improved Synlam™ substrate: 0.5 waves

Processes for Replica Optics: Mirrors on MMC Substrates

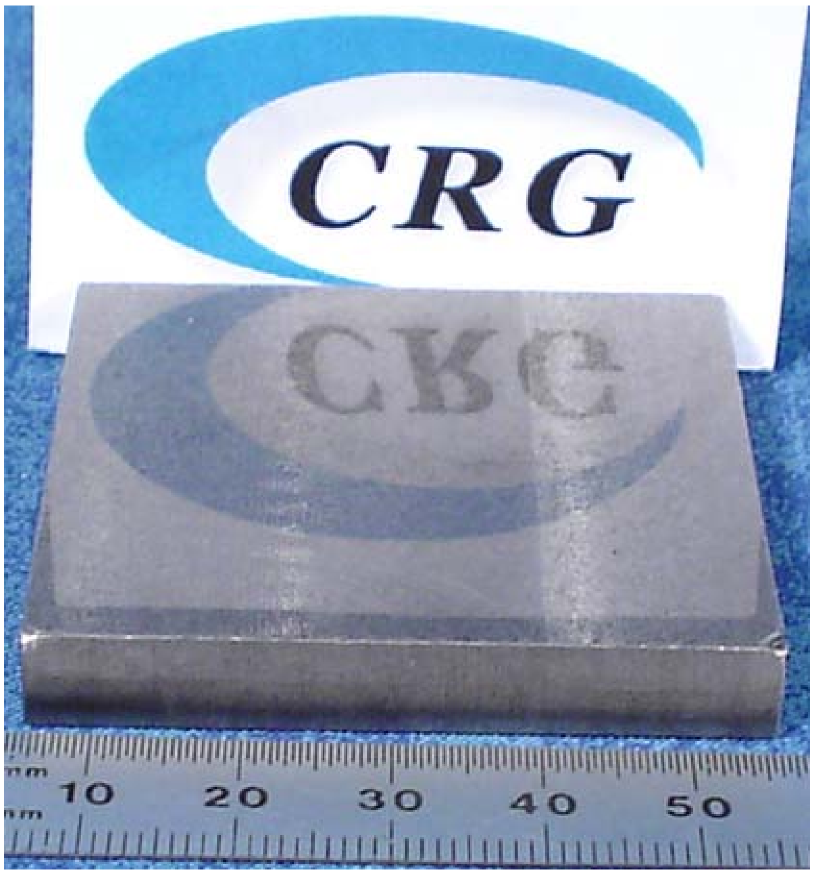
- **Carbon syntactic replication layer on MMCC Inc MetGraf 2 metal matrix composite**
- **Figure: 2.23 waves RMS; finish: ~64 nm RMS**

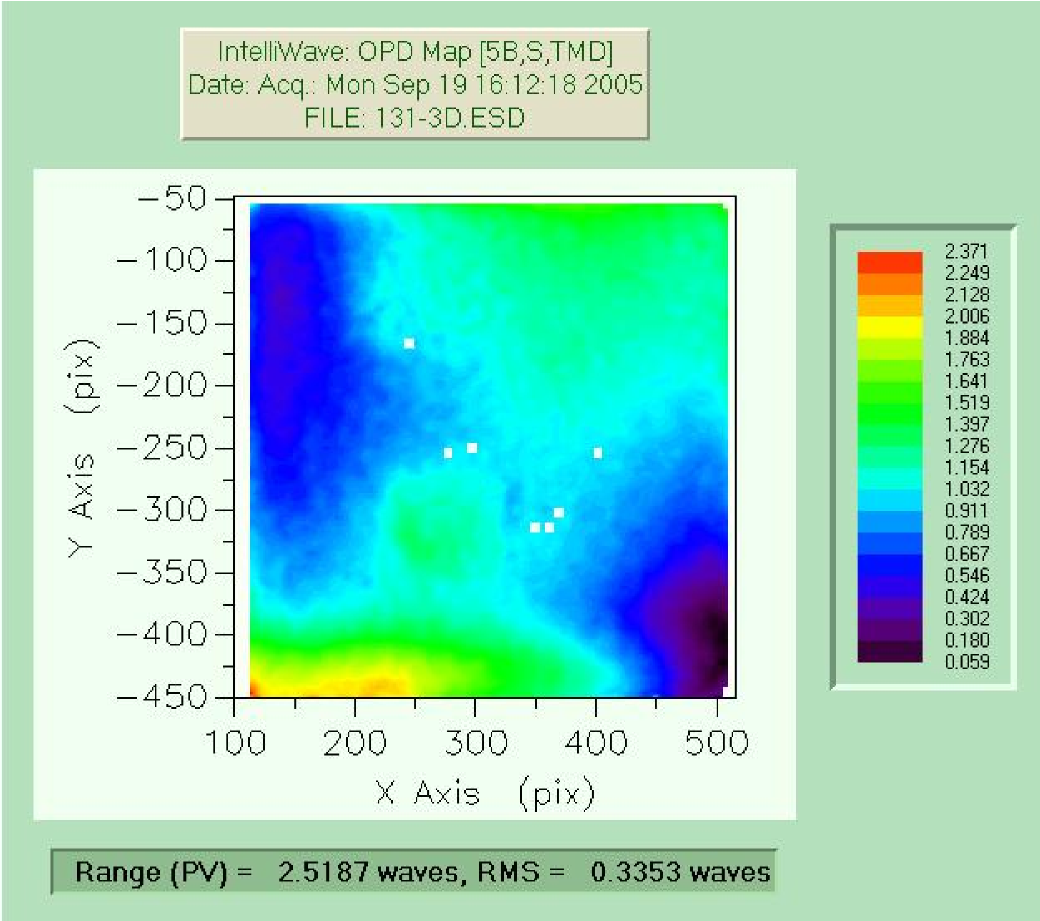




Processes for Replica Optics: Mirrors on MMC Substrates

- **Epoxy replication layer on MetGraf 2**
- **Figure: 0.34 waves RMS; finish: 13.4 nm RMS**





Processes for Replica Optics: Nanolaminate Replica Concept

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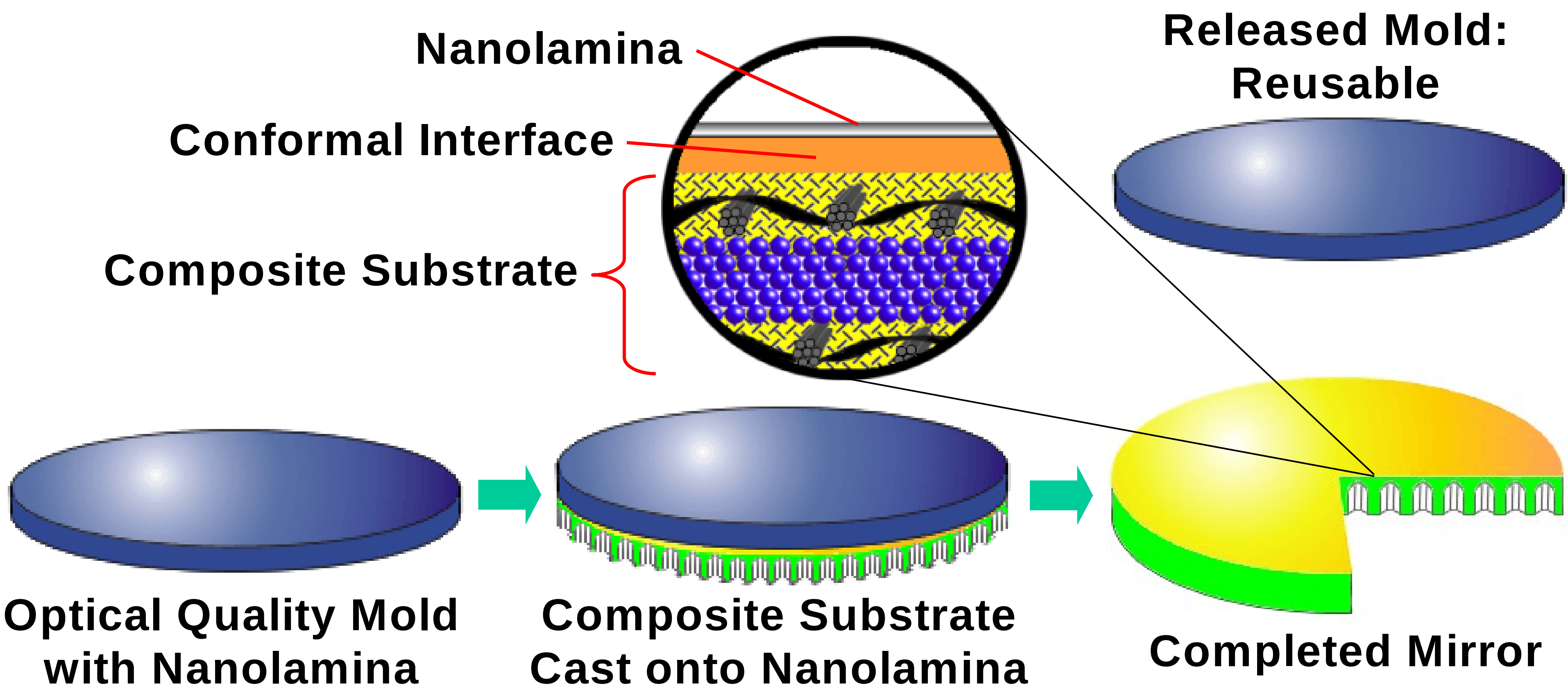
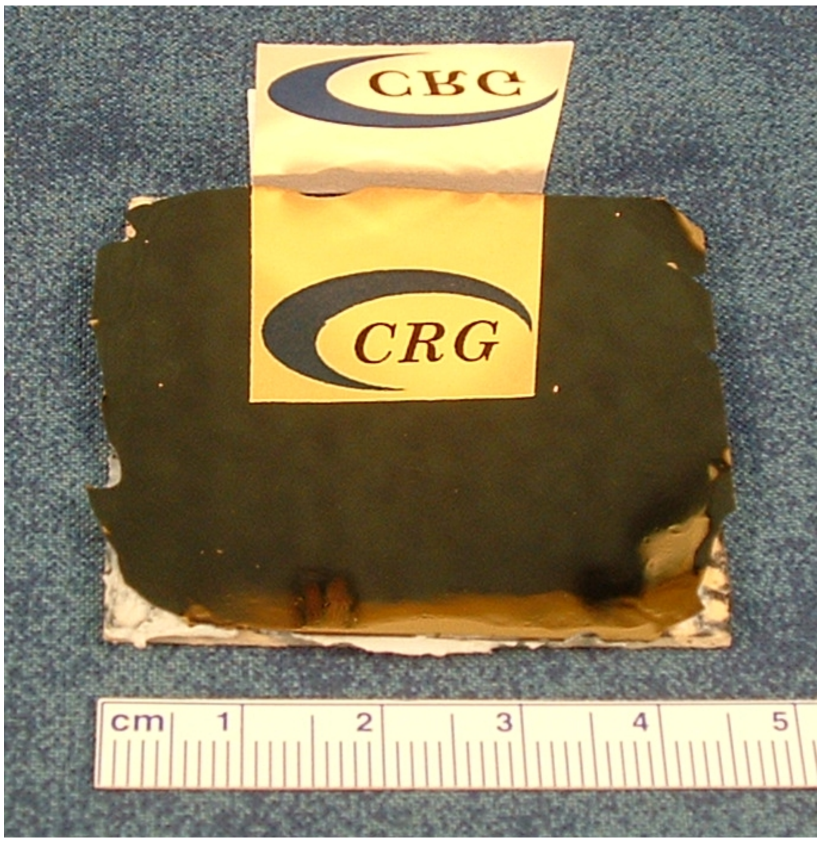
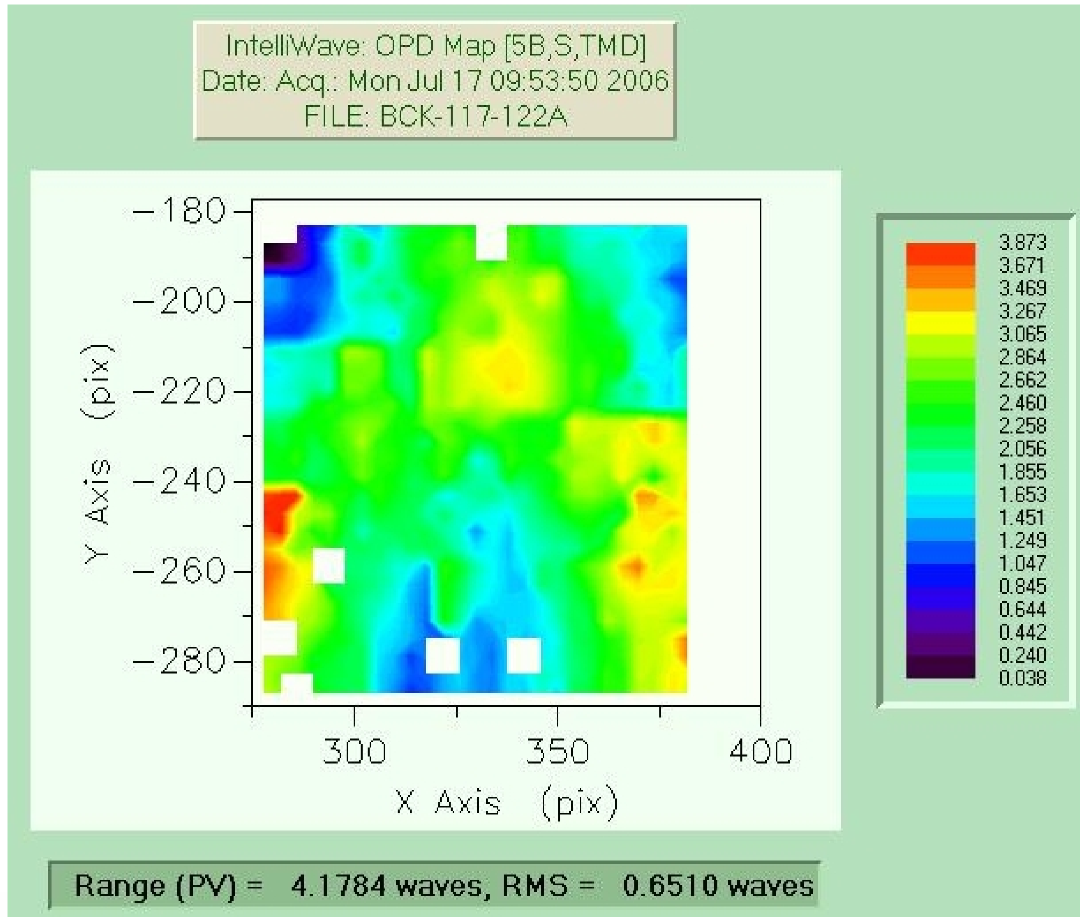


Processes for Replica Optics: Nanolaminated Synlam™ Mirror

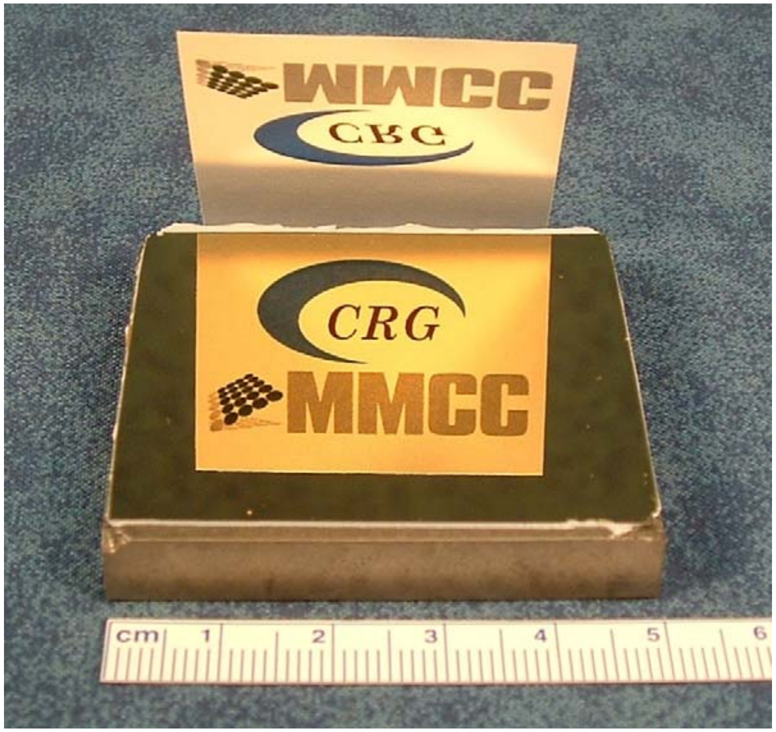
- Synlam™ with nanolaminate from Lawrence Livermore National Laboratory (LLNL)
- Figure: 0.65 waves RMS; finish: 50 nm RMS

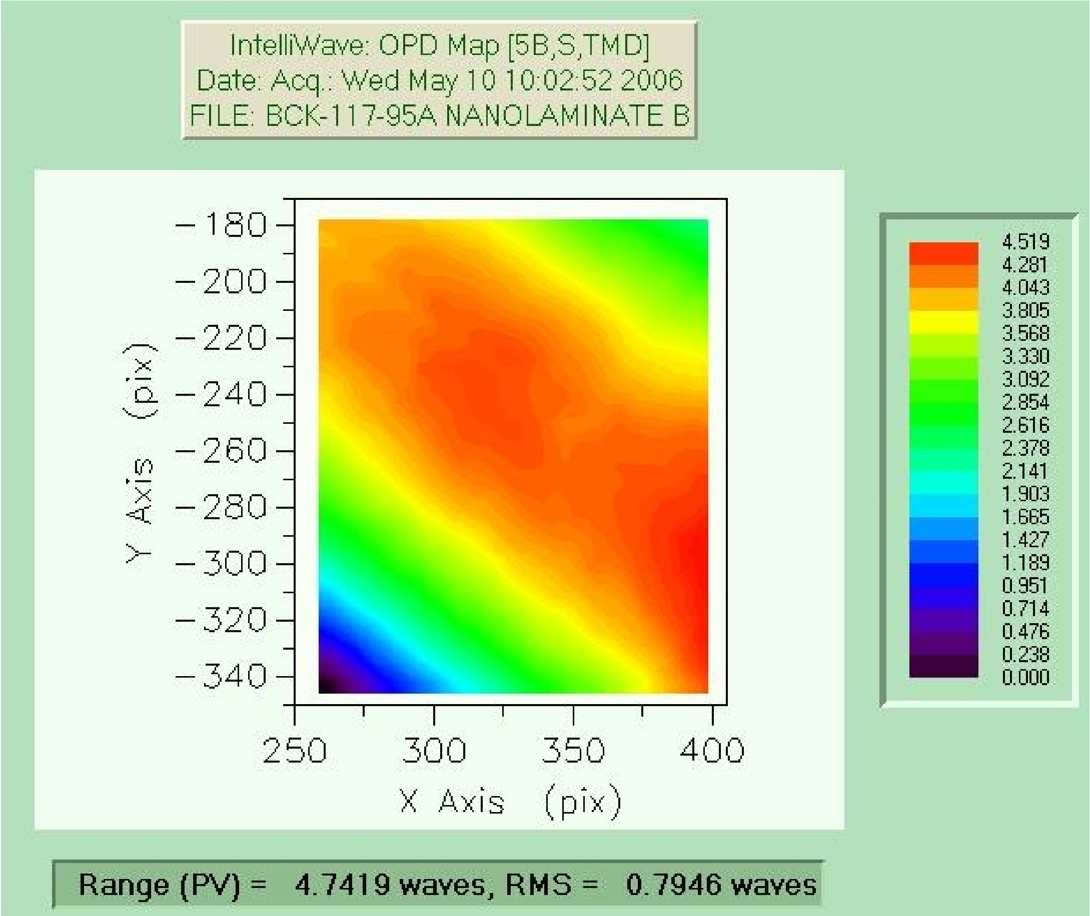




Processes for Replica Optics: Nanolaminated MMC Mirror

- **MetGraf 2 with LLNL nanolaminate**
- **Figure: 0.8 waves RMS; finish: 4.59 nm RMS**





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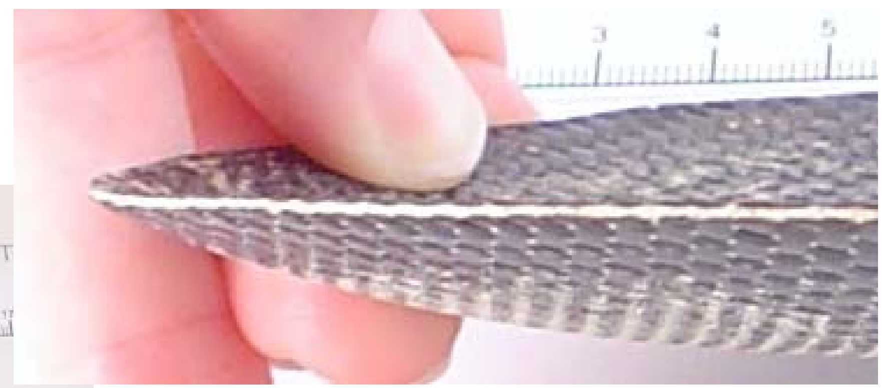
Mirror Structures: Monolithic Synlam™

Process development:

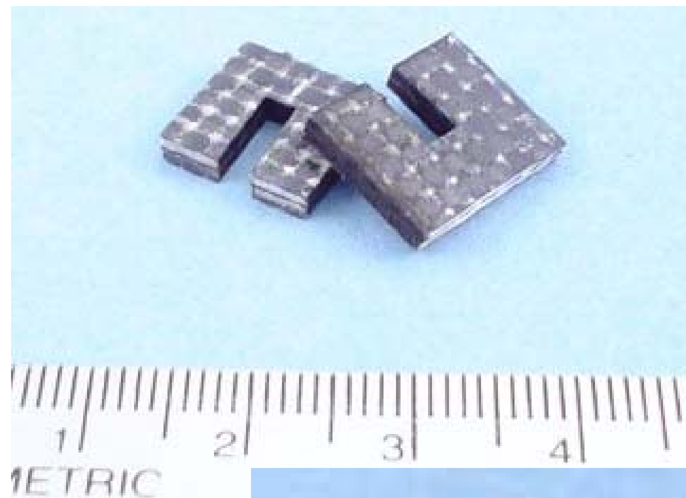
Complex Synlam™ Structures

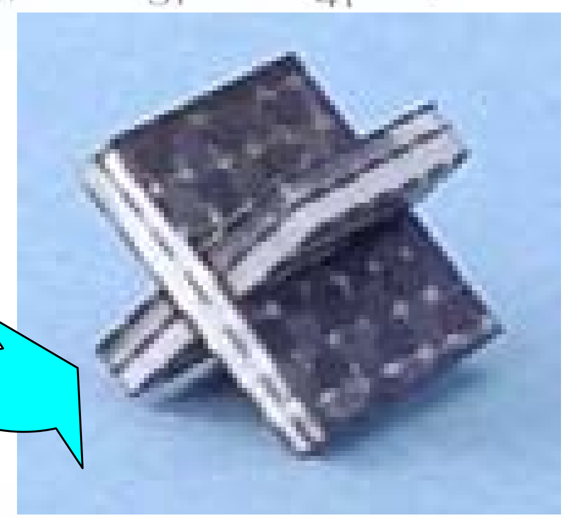


Mirror Structures: Assembled Synlam™

Process development:

Precision cutting & joining





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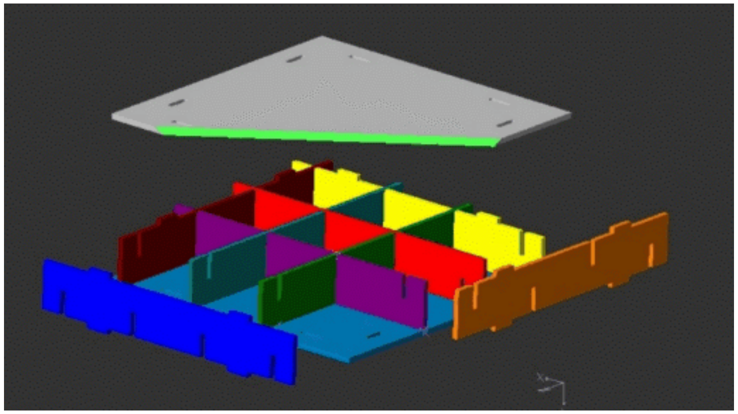
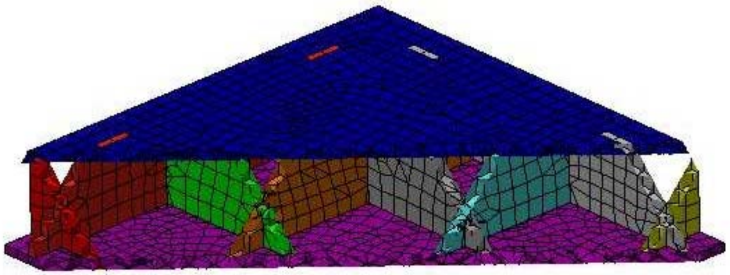
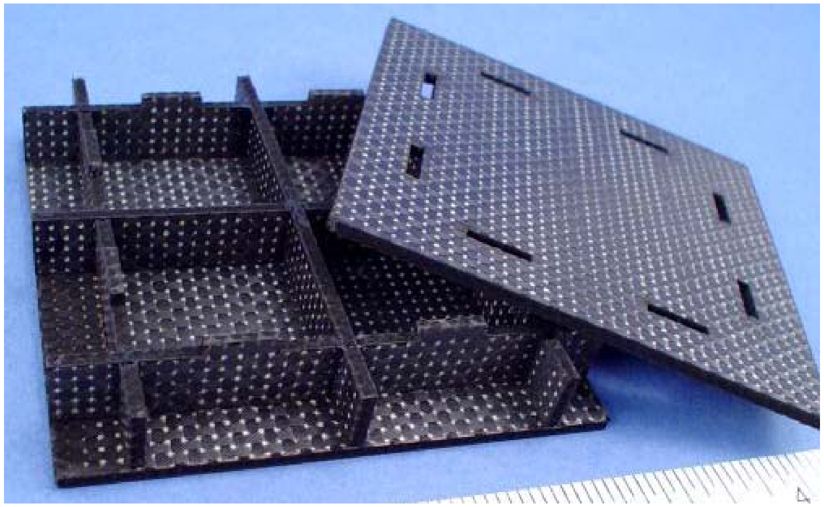
Mirror Structures: Assembled Synlam™



Design



FE Analysis



Fabrication

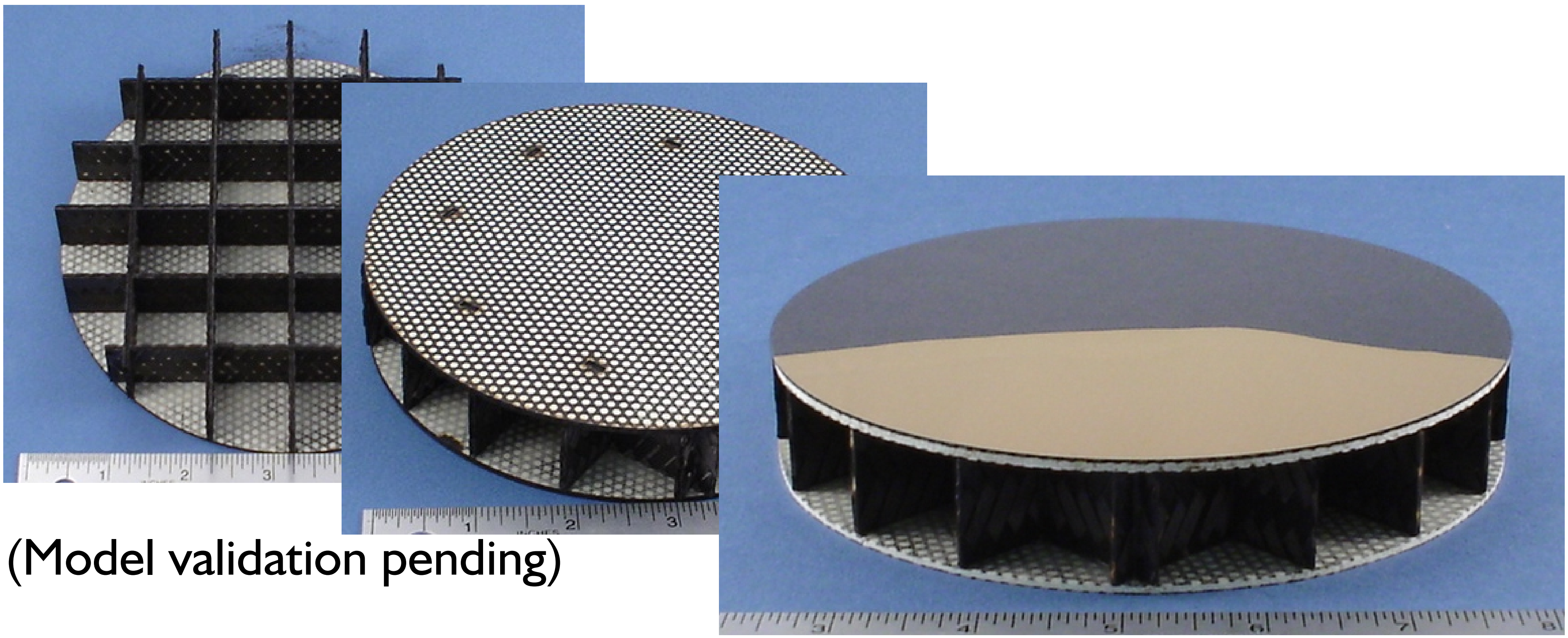
Synlam™ Structure

(8 cm across)

Areal Density 3.2 kg/m^2

Mirror Structures: Assembled Synlam™

- First mirror structure assembly
- Glass face sheet, analog for nanolaminate



(Model validation pending)

Areal Density without face sheet = ~4 kg/m²

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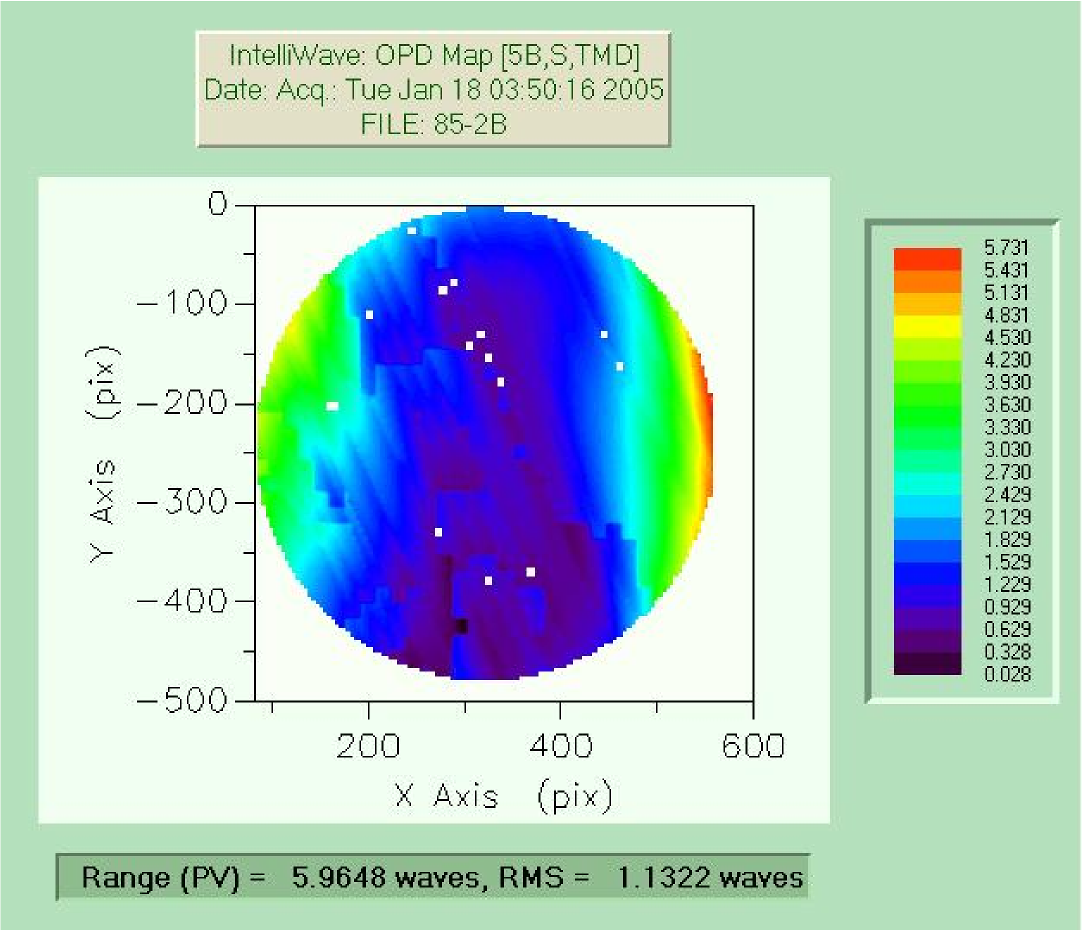
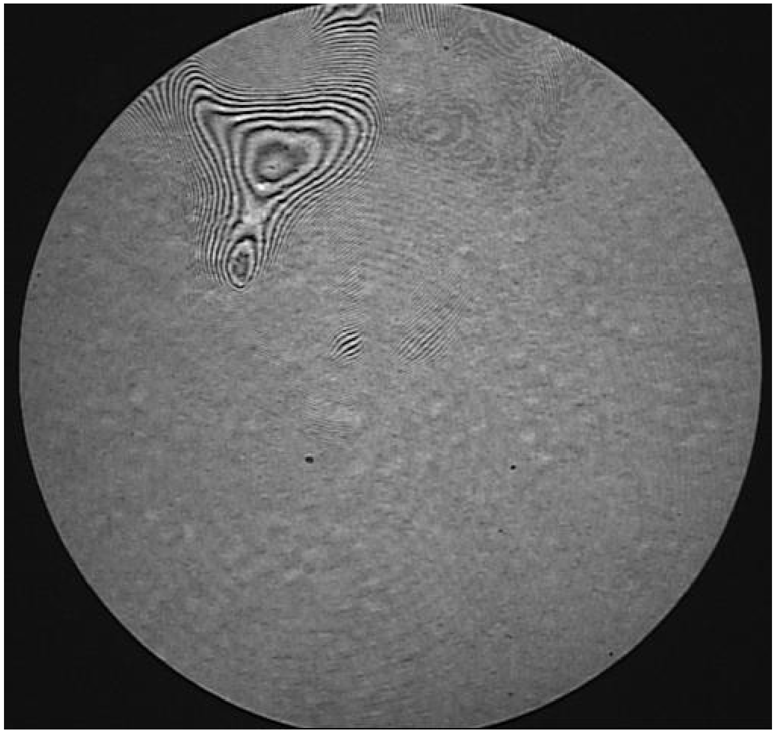
Mirror Structures: Assembled Synlam™



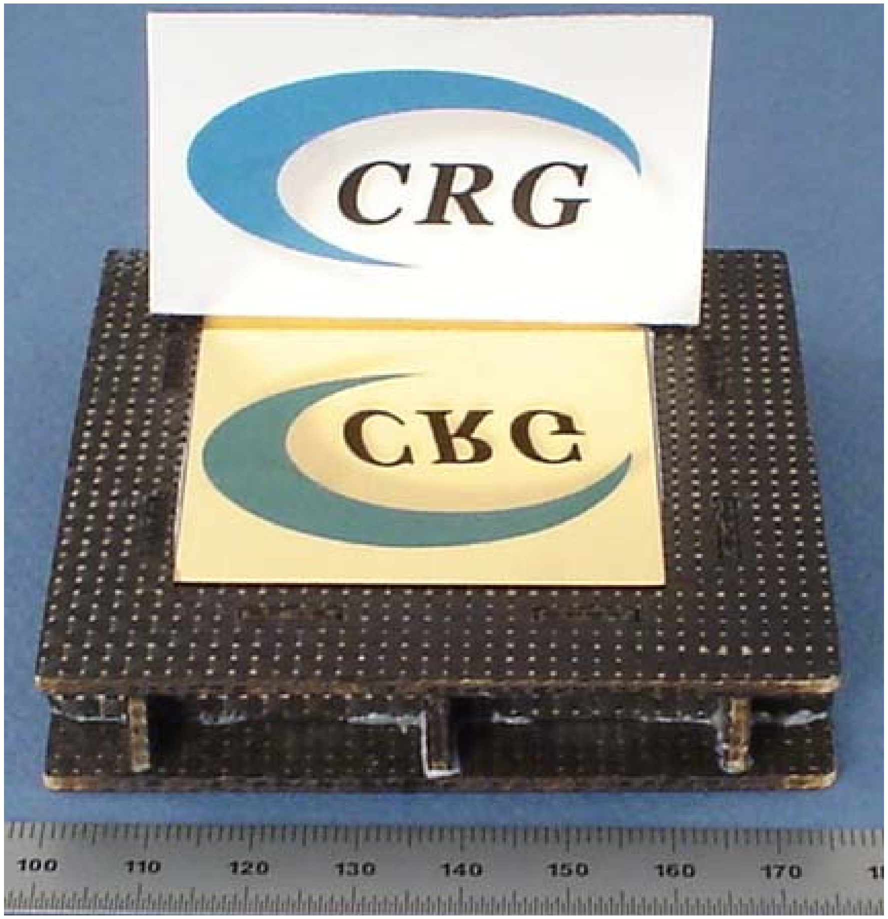
Face sheet before bonding



Face sheet after bonding

- Quilting effect
- Improvement required
  - Adhesive
  - Assembly technique

Mirror Structures: Nanolaminated Synlam™ Mirror



Areal Density:
8.4 kg / m²
(incl non-reflective margin)

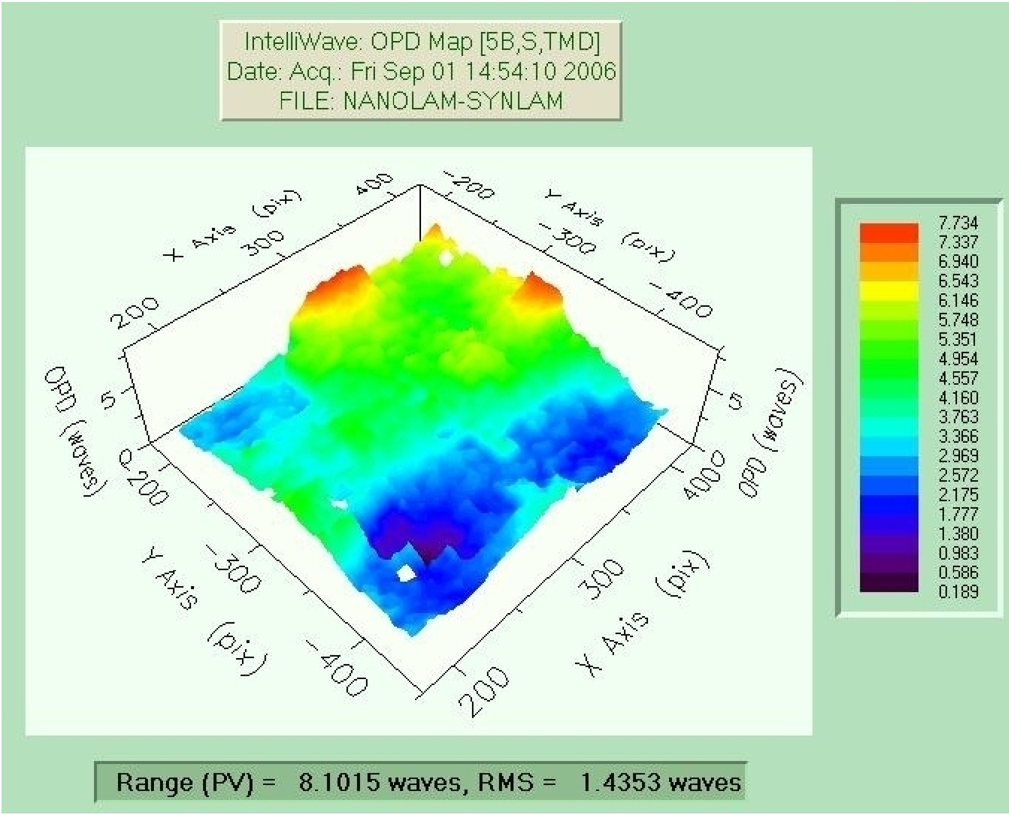


Figure 1.44λ RMS

Finish 87.1 nm RMS

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Overview

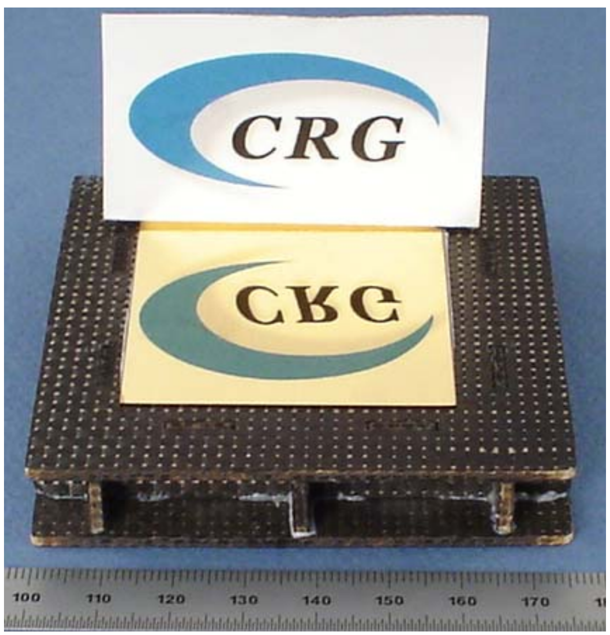
- Introduction
- Materials
- Processes for Replica Optics
- Mirror Structures
- Summary

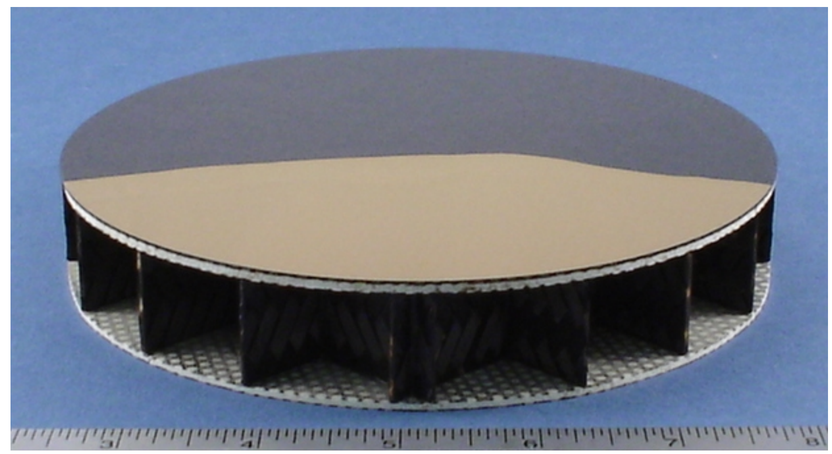
Summary

- **Sialyte™ Inorganic Composites**

  0 CTE space-compatible material

- **Cyanate Ester Organic Composites**
  - Synlam™ high-specific stiffness, lightweight material
  - High-performance syntactic foam





- **Replication Processes**
  - Thermoset cast on substrate
  - Nanolaminate on substrate

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Summary

Composite Replica Mirrors for Lightweight Space Optics

- Operational Benefits
  - Reduced mirror areal density
  - Tougher & stronger mirrors
  - Reduced fabrication time & cost
- Potential Air Force Applications
  - Space-based imaging systems
  - Space-based directed energy systems
- Potential Commercial Applications
  - Commercial imaging systems
  - Consumer telescopes